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OF

MATERIALS OF CONSTRUCTION

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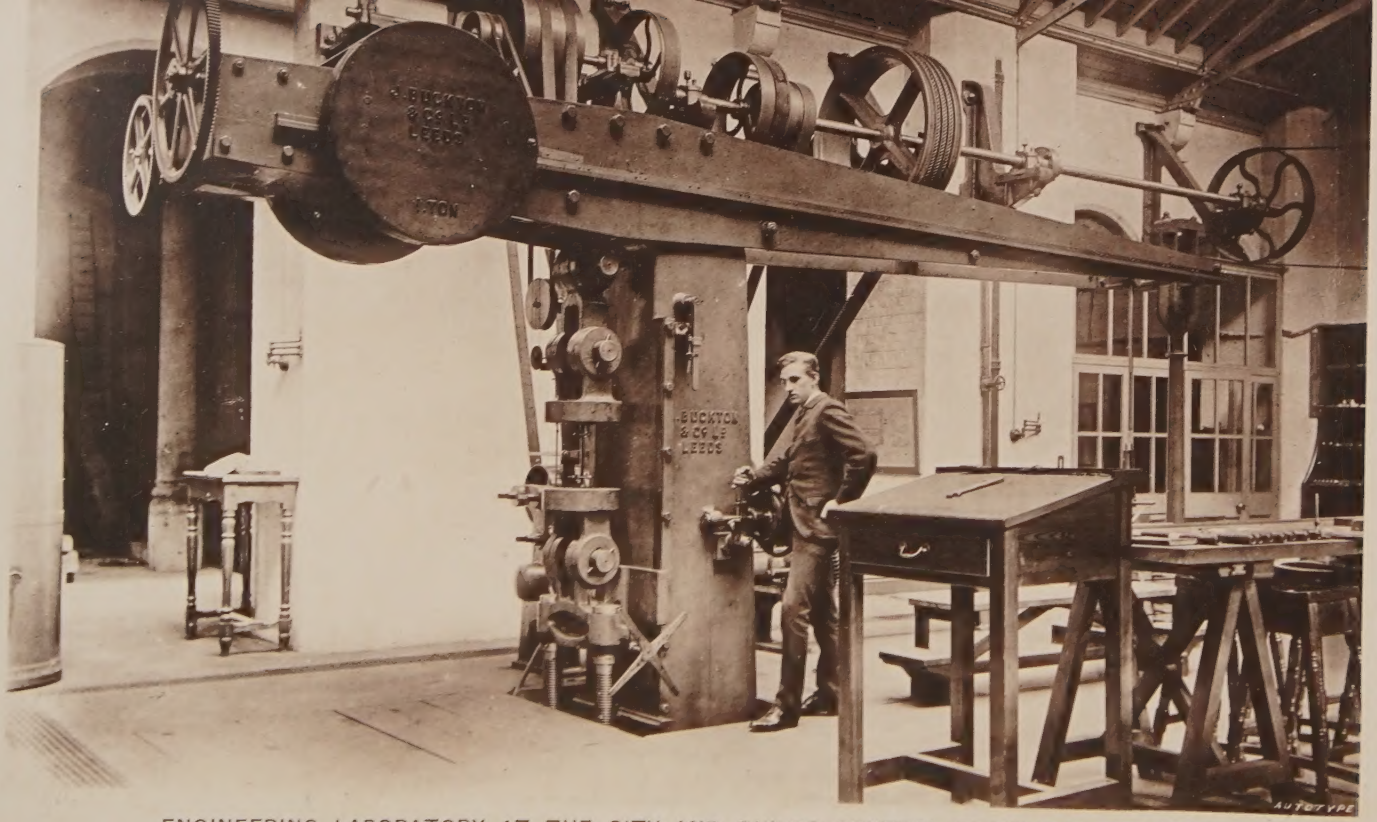

ENGINEERING LABORATORY AT THE CITY AND GUILDS CENTRAL TECHNICAL COLLEGE.

THE TESTING

OF

MATERIALS OF CONSTRUCTION

A TEXT-BOOK FOR THE
ENGINEERING LABORATORY AND A COLLECTION OF
THE RESULTS OF EXPERIMENT

BY

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THE ROYAL INDIAN ENGINEERING COLLEGE

WITH 5 PLATES AND 206 DIAGRAMS

THIRD EDITION

LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
NEW YORK, BOMBAY, AND CALCUTTA
1910

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PREFACE

TO

THE THIRD EDITION

The present work is a treatise on the Strength of the Materials used in Construction, considered in connection with the instruments and methods by which the mechanical properties of materials are investigated experimentally.

The data on which the engineer relies in designing structures cannot be fully understood without some knowledge of the procedure by which they are ascertained. Also, for several reasons, a knowledge of the methods of testing has become of late of greater importance. A considerable advance has been made in the construction of all the apparatus used in testing, the operations of testing are carried out with increasing care and skill, and much discussion has taken place as to the relative value and importance of different tests. The establishment of well equipped laboratories in connection with schools of engineering has made experimental investigation an essential part of Engineering Education.

This treatise consists of three parts. In the first the mechanical properties of materials are explained, that is the phenomena of elasticity and plasticity and the relations of stress and strain, so far as they have been scientifically ascertained. In the second, the apparatus used in the Engineering Laboratory is described. The third part contains a collection of the most complete and trustworthy

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results of testing of all the ordinary materials of construction. The mass of data accumulated in about half a century is enormous. It seemed to be historically just in cases where laws were first established by adequate experiments to refer to the original investigation. But unquestionably more recent researches have been carried out with better appliances and with greater skill and knowledge. The results given in the tables have been reduced to common units so as to be readily understood and compared, and in some cases new relations between the observed quantities have been calculated.

Since the publication of the second edition twelve years ago a large amount of investigation has been carried out. New apparatus has been constructed, and fresh light has been thrown on many subjects. The work of the British Standards Committee, in discussing methods of testing, selecting tests of quality, and fixing standard specifications, is of great value and importance. The International Testing Association, founded by Bauschinger, has also done much to improve and standardize methods of testing. The treatise has been very carefully revised, and it is hoped that an account of all important results of the more recent investigations has been included.

KENSINGTON, *March* 1910.

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THE TESTING

OF

MATERIALS OF CONSTRUCTION

INTRODUCTION

The arts of construction probably arose out of simple need of shelter, and in house-building men were first driven to apply natural materials to purposes involving the consideration of their mechanical properties. As communities were formed and social relations became more complex, the builder's art developed and extended. Roadways were necessary for traffic, temples for worship, fortresses for defence.

Now, in all works of construction are involved questions of the strength and rigidity of materials. In the rudest house-building, materials must have been selected because they were strong, and proportioned with some reference to the forces to which they would be subjected; with every increase of size and complexity in the structures erected, reconsideration was necessary of the materials available, and more attention would be given to securing adequate strength and stiffness. Other considerations would have weight. Granite might be chosen for durability, marble for polish, bronze for lustre, gold for costliness, metal to be beaten, wood to be carved. But in no case could considerations of strength be entirely ignored. The forms which give character to mediæval architecture—arch, buttress, groin, and tracery—are due to the desire to obtain great structural strength consistently with other requirements. And amongst those other requirements one must always have been to economise the amount of material used.

It is, however, under the pressure of quite modern necessities that the problem of using materials to the greatest

advantage in securing strength has come to be before all other considerations in the mind of the designer. In modern structures and machines, whatever other objects are in view, the designer has always to consider what are the straining actions to which the structure will be subjected, and what is the safest material, and the best disposition of it, and the least amount of it necessary to resist those straining actions.

The cause may be the increased value of labour, or the greater use in construction of artificial or manufactured materials, or the greater scale of modern works, or the commercial conditions under which they are undertaken. Whatever the cause, the modern engineer or constructor has always to consider what is the cost of the material required to give adequate strength.

The simplest mode of ascertaining the safety of a structure, say of a steam boiler, or a bridge, is to apply to it a testing load greater than the maximum load to which it is likely to be subjected. To a certain extent this testing of completed structures is, and always will be, carried out. Before a boiler is put under steam it is tested by hydraulic pressure ; before ordinary traffic passes over a railway bridge, a heavy train load is placed on it. Such tests sometimes reveal unknown or unsuspected sources of weakness. But little information is derivable from tests of completed structures, from the necessary limitation of the testing load. No load can be applied likely to injure or deform the structure, unless it is quite seriously ill proportioned or ill constructed. And an extreme testing load may damage a structure, such as a boiler or bridge, without any possibility of the injury being detected at the time. It would also be very inconvenient if structures were erected at hazard with a chance of breaking down under the testing load. Such tests of completed structures have become to a certain extent superfluous. They are useful as affording a final guarantee of security, but they do not supply specific information as to the margin of safety which exists. In by far the largest number of constructions no testing load can be applied except the ordinary working load.

It is here that purely theoretical studies come to the assistance of the engineer. For the materials he uses, the deformations due to the stresses are small, and within working limits of stress they are very nearly proportional to the stresses. Assuming the deformations to be small and proportional to

the stresses, it is possible to reduce the straining actions in the most complex structures to comparatively simple straining actions in their separate members. With that part of applied mechanics which deals with the determination of the simpler straining actions on the members of complex structures we have not in this treatise to deal. Supposing, however, this analysis made, then experiment on pieces of material subjected to such simple straining actions will show how the members of complex structures should be proportioned. Hence, for a hundred years or more, engineers have been constantly experimenting on small pieces of different materials subjected to simple straining actions. Experiments of this kind are called tests of the strength of the material, and the machines for making these tests are called testing-machines.

There are two distinct objects in view in subjecting materials to mechanical tests. The one is scientific, the other commercial. When the object is scientific, the experimenter aims at the determination of the physical constants of the material and at verifying the assumptions on which theoretical calculations proceed. When the object is commercial, the experimenter endeavours to ascertain whether samples of a material comply with certain more or less arbitrarily chosen standards of quality. That the methods of testing for scientific and for commercial purposes more or less coincide should not be allowed to obscure an essential difference. Absolute results are wanted in scientific testing, relative results in commercial testing. What is the elastic limit, the modulus of elasticity, the safe limit of stress in given conditions of a given material, are questions in the one case. Which of two samples of materials is the better sample on the whole, is the kind of question in the other case.

Scientific Testing.—The object of scientific testing being to determine the physical constants for a material, it will be useful to enumerate those which, for the purposes of the engineer, are most important.

The definite physical constants required in the application of theories of the resistance of materials are the following:

1. *Density* or heaviness. A great part of the straining action in most structures is due to the weight or inertia of the structure itself. Besides this, in many materials the density is directly connected with other properties of the material. In the case of porous or granular bodies, it is sometimes

necessary to distinguish the real density of the material and the apparent density due to the space it occupies.

2. In machines some parts slide or roll on others and the friction causes wear. Hence for some purposes and for certain materials it is useful to determine the *hardness* or resistance to abrasion.

3. *Coefficients of elasticity* or ratios of stress to strain. For practical purposes it is usually accurate enough to assume a material to be elastic, homogeneous, and isotropic. In that case its deformation by any straining action can be determined if two elastic coefficients are known—the coefficient of elasticity of form, and the coefficient of elasticity of volume. But, for application, other elastic coefficients dependent on these are also convenient. These coefficients are required for two reasons. A structure must be designed so that not only does it resist the straining action without breaking, but also without prejudicial deformation, and the elastic coefficients are required to determine the deformations from the stresses. Next, in many cases the stresses depend on the deformations and the coefficients of elasticity appear in the equations for determining the stresses.

4. *Limits of Elasticity.*—An elastic material is one in which the deformations are proportional to the stresses, and vanish if the straining action is removed. Certain materials, like cast iron, are not perfectly elastic in their initial condition for any straining action. They are permanently deformed, or take a permanent set, with very small loads. But many materials are almost perfectly elastic, between an upper and lower limit of stress, and most important materials of construction become so, after being strained, for a certain range of stress. It is only within that range of stress that the ordinary rules of strength of materials are strictly applicable. The limits of elasticity must be known to determine the extent to which the rules can be trusted.

If the two limits of elasticity of a material were fixed by the conditions of its manufacture, the modulus of elasticity and limit of elasticity, once directly ascertained by experiment, would furnish all the data necessary to the engineer in applying the theory of elasticity and fixing the working limits of stress. That, however, is not the case and the limits of elasticity are not so stable as has been generally supposed. Subjected to cyclical variations of stress between definite limits new elastic limits are established, which may be both

in tension, or both in compression, or more generally one in tension and one in compression. There are probably corresponding limits for shearing stresses, but these have been less investigated.

One of the most ordinary conditions of a structure or machine is that it is subjected to reiterated working stresses, all lying between a minimum and maximum value of one kind of stress, or between a maximum stress of one kind and a maximum of the opposite kind. In such conditions, new elastic limits are produced differing from the original or primitive elastic limits. The determination of what those limits are in given circumstances is the object of remarkable and difficult researches, which are beyond the range of ordinary testing.

No doubt it is accurate enough for practical purposes to treat ordinary structures and machines as perfectly elastic, and to determine the distribution of stress on that assumption, for experience has fixed the limits of working stress far within the primitive elastic limits. But it is by no means clear that the working stress is commonly so fixed as to secure equal safety in different cases, and, if the proper working stress is to be determined on rational principles, the study of the conditions in which the elastic limits change becomes essential.

5. *Breaking Stresses.*—In the case of solid materials an increasing load produces an increasing deformation. Generally, a limit is reached at which the bar suddenly fractures. Under defined conditions of loading—for instance, with a gradually increasing statical load applied in a short time—the breaking stress, reckoned per unit of area, is a perfectly definite constant for a material, and is to a great extent independent of the form and dimensions of the bar tested.

As ordinarily stated in tables of strength of materials, the so-called statical breaking stress is a somewhat fictitious quantity. Most constructive materials are ductile. Suppose a bar of ductile material subjected to tension. It will be found that a maximum load is reached before the bar breaks. At that point the elongation becomes very rapid and the section rapidly diminishes. The bar will no longer support the maximum load, and it finally breaks with a load 10 or 20 per cent. less than the maximum load. What is ordinarily understood as the breaking stress is the *maximum load* divided by the *initial sectional area* of the bar. That is, it is

a load which is not the breaking load, estimated on an area which no longer existed when the bar broke. There are, of course, reasons of convenience for estimating the breaking stress in this way, and no error need arise if the mode of estimating the breaking stress is remembered.

But, further, the early experiments of the Railway Commission, the experiments of Fairbairn for the Board of Trade on a small plate girder, the splendid series of researches by Wöhler, continued by Spangenberg and Martens, and confirmed by similar experiments of Bauschinger and others, all show that bars subject to cycles of varying stress break with loads of from one-half to two-thirds the statical breaking stress. The greater the range through which the stress varies, and the greater the number of repetitions, the lower is the breaking stress. These results are explainable if it is supposed that, instead of fixed limits of elasticity, these limits depend on the range and kind of variation of stress, and that, if the range of perfect elasticity possible in given conditions is exceeded, deformations are produced which, accumulating with successive repetitions of load, finally lead to fracture. General experience accords with this conclusion. Under a purely statical stress, a bar not too ductile would probably be safe with seven-eighths of the ordinary so-called breaking stress. But with a varying load no working stress as high as that would be safe. If the range of variation is small, the working stress may still be comparatively high. The Conway Bridge, in which the rolling load is small compared with the permanent weight of the bridge, is subjected daily to stresses reaching 7 tons per square inch, or nearly one-third of the breaking stress. But ordinary iron or mild steel bridges with a larger proportion of rolling load, and therefore a greater variation of stress, are not subjected to more than 5 tons, or at most a fifth of the statical breaking stress. Even this limit proves to be too high for bridges of very short span, in which the range of variation of stress is greater. Ordinary mild steel shafting and axles are rarely loaded beyond 4 tons to the inch, and in many parts of machines subjected to alternating tensions and compressions the stress does not exceed 2 tons per square inch, or one-twelfth of the breaking stress.

It has been common to assume that the margin between the calculated working stress and statical breaking stress, as determined by ordinary testing, is merely an allowance for

contingencies. But it is in no way clear that, in cases where this margin is in practice greatest, the probability of the working stress being exceeded is greatest also. Further, the need of an allowance of 400, 600, or 1,100 per cent. for mere contingencies neglected in calculating the stresses in the structure is incredible. It is much more probable that the elastic limit really fixes the safe limit of working stress, and that this varies with the range of variation of stress.

Hence, besides the ordinary so-called breaking stresses determined in ordinary statical testing, it is distinctly one object of scientific testing to determine the breaking stresses under conditions of variation of stress, and especially to ascertain the conditions of time under which such variations of stress are effective in altering the breaking stress.

But besides these dynamical conditions which affect the physical constants of a material, it is the object of scientific testing to determine how far different conditions of manufacture, of mechanical treatment, of microscopic structure, of chemical constitution, of temperature, and so forth, affect the physical constants of the material, and inferentially its value as a material of construction. It is by researches of this kind that guidance is obtained in seeking the improvement of any given manufacture.

6. *The Yield Point.*—In iron and steel, when tested for the first time and in some other rolled or hammered materials, at a stress exceeding more or less the elastic limit, there occurs a large and almost sudden increase of deformation and the deformation is chiefly permanent or plastic deformation. For greater stresses the plastic deformation increases, and it amounts, before fracture is reached, to many hundred times the whole elastic deformation. The point at which this almost sudden augmentation of plastic deformation occurs is termed the yield point or breaking-down point. It is now known that this yielding in crystalline but ductile materials, such as mild steel, is due to deformation of the crystals by slips along the natural cleavage planes. It is obvious that a general plastic yielding of a structure would ruin it for practical purposes, hence the yield point seems to fix a limit of stress independent of that determined from considerations of safety against fracture, which the working stress should not exceed. The yield point is raised by loading which exceeds the primitive yield point, but it is not usually practicable to raise the yield point of a material artificially

before using it in a structure, and consequently the primitive yield point, due to the mechanical operations of manufacture, fixes with respect to deformation a dangerous limit of stress. But the case is not quite so simple as at first it appears. In almost all actual structures the maximum stresses are confined to very limited portions of the structure. It is not quite clear that a riveted joint is either sensibly deformed or permanently injured, even if the yield point at the dangerous section is exceeded. In testing large riveted girders the deflections are regular and proportional to the loads, almost to the breaking weight, and show no indication of a yield point.

By careful scientific testing, most of the constants enumerated above have been determined for the various materials which are used by the engineer. But a question arises which should not be entirely passed over. How far do such tests as have been made afford a trustworthy foundation for the wide extension which is given to their results by the aid of applied mechanics? It is, perhaps, desirable at least to point out some of the differences between the conditions of even the most careful testing and those which obtain in engineering structures. In the first place, most experiments have been made on test specimens of very small size; and it is not always safe to infer that the material in the small test bar, and that in the large structure, are of identical quality and in precisely similar conditions. In the case of timber, for instance, Professor Lanza's experiments show a wide discrepancy between small and large specimens. In another respect, at least, there is still a considerable difference between engineering structures and ordinary test bars. Engineering structures are almost always compound structures made up of mechanically connected parts. To what extent a compound structure of that kind can be taken to be equivalent to a simple homogeneous structure is, at present, at least so far as direct experiment is concerned, imperfectly known. Happily the very defect of elasticity in ordinary materials tends to diminish the variation of stress in compound structures, which is due to imperfection of the mechanical connections, which induces locally excessive stresses. But it is probable, and, to a certain extent, it is in accordance with practice, that the limiting stress should be rather lower in a compound than in a simple structure; that stresses, for instance, are safe in a simple railway bar or axle, which under similar conditions would be unsafe in a riveted girder. The differences between

ordinary tests and actual structures as to time and frequency of repetition of load have already been spoken of. Lastly, in many actual cases in practice, the parts of a structure are subjected to combined normal and shearing stresses, and it is only recently that much progress has been made in investigating experimentally the failure of materials subjected to compound stress.

Commercial Testing.—The materials used by the engineer are natural or artificial products, and generally several sources of supply are available. It is important to be able to distinguish the quality of the materials coming from different localities or from different manufacturers, or which differ considerably in grade or cost. A manufacturer may be skilful or careless; may use good raw materials or bad raw materials; or accidental circumstances may interfere with the processes of manufacture. The conditions involved in the success of a manufacture are numerous and complex. No mere supervision of the processes or external examination of the resulting product is an adequate guarantee of quality.

Now, the engineer requires to know if he is getting material good of its kind, and suitable for the purpose intended. To determine this no method is so convenient or safe as the selection of sample portions of the material, which are then subjected to appropriate tests, and since a rapid and definite judgment is required, more or less arbitrary standards of quality must be accepted. Qualitative or comparative testing of this kind may be called *Commercial Testing*, to indicate its character without any intention of depreciating its importance.

Since the physical constants of a material really determine its value for constructive purposes, commercial tests may be made to approximate as closely as is practicable to tests for scientific purposes. But this is by no means always convenient. Shorter and readier methods are often sufficient for comparative purposes. What the user of a material requires to know is whether a material supplied is as good as material previously employed in similar cases; or, of two materials equally available, which is the better. Generally he is content to adopt one or two easily applied tests, and to judge by comparison of the results of these alone. All that needs to be noted at present is that these commercial standards of quality are often arbitrary to an extent which has been too much overlooked.

Again, it is sometimes convenient to make chemical analyses of materials instead of mechanical tests. No doubt the physical properties of a material are often closely connected with, and can, to a certain approximation, be inferred from its chemical composition. Particular defects, such as adulteration, are better detected by chemical analysis than by mechanical tests, and in some cases particular constituents have a definite effect on quality. Sulphur and phosphorus are prejudicial when present in iron. The physical properties of steel depend somewhat closely on the amount of carbon, silicon, and manganese it contains. Lime and gypsum are sometimes mixed with cement, and injure its quality. But, in fact, the engineer has to do with the mechanical properties of materials; and the indications furnished by chemical analysis, though valuable, are indirect, and not for the engineer's purpose completely reliable. Steels made from the same raw materials, and having identical chemical constituents, may, from difference of mechanical treatment and other causes, have differences of quality of importance to the engineer.

In selecting materials for his construction the engineer is really concerned only with their mechanical properties, their strength, toughness, hardness, or adaptation to the mechanical operations of the workshop. To characterise these mechanical properties certain simple tests have been adopted such as tensile tests, bend tests, &c., and experience shows that though these are to some extent empirical, they suffice, in all but very exceptional cases, to detect bad or unsafe material. It is in the case of steel that a careful system of testing is of the greatest importance, because in steel the mechanical properties vary through a wide range and small differences in composition or thermal treatment cause great differences in its suitability for construction.

What tests of strength and toughness are commonly adopted will be discussed later on. Down to a recent period the test conditions in different specifications for the same material differed greatly. Different engineers had different views as to the relative importance of the qualities required and as to the tests which were trustworthy, or acting without concert unintentionally imposed discrepant conditions. No manufacturer objects to adequate testing and inspection of the material he produces. But he has a right to object to have to meet different test requirements for the same material, intended for the same purpose, supplied to different users.

It is a matter of experience and investigation to determine what are the necessary and the best test conditions for a given material for a given purpose. Unnecessary and discordant test conditions hamper the manufacturer and add to the cost at which the material can be supplied.

The British Standards Committee have now drawn up a series of complete specifications for different materials most used in engineering construction. These cover all the necessary checks on quality and the test requirements suitable in different cases.

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CHAPTER I

MECHANICAL PROPERTIES OF BODIES ACTED ON BY STRESSES

The system of external forces to which a body or structure is subjected, due to its own weight, or the weight of loads it supports, or to pressures transmitted to it from other bodies, or to other causes, may be termed the straining action. Every straining action produces alterations of shape or volume in the body subjected to it. The molecular forces in the body which resist deformation are termed stresses, and the deformations due to straining action are termed strains. One principal object in testing operations is to determine the relation of the stresses and strains.

A hanging chain supporting a load is subjected to a straining action due to the load and the reaction at the point of support. Each link is subjected to a straining action due to the pull of the two adjacent links. At any cross-section of a link, the molecular forces, resisting the separation of the two segments into which the section divides the link, form a stress, which may be regarded as the action of either segment on the other, or as the resistance of either segment to the action of the other. The elongation of the link due to the pull of the adjacent links is the most obvious of the strains due to the straining action.

1. *Elastic and Plastic Materials.*—The most important distinction in solid bodies, from a mechanical point of view, is that some are elastic and others imperfectly elastic. Elastic bodies recover their form after the straining action is removed or the stress and strain arise and vanish simultaneously. Imperfectly elastic bodies are permanently altered in shape or volume by a straining action. Brittle bodies are those which break in pieces under a straining action before there is any great alteration of shape. Other materials can be greatly deformed without losing continuity or breaking into

fragments, and these are termed malleable, ductile, or plastic, according to the mode of application of the stress. Gold is beaten into leaves, copper is drawn into wire, clay is moulded by pressure.

The word which best expresses the property of suffering an indefinitely large permanent deformation is the word plastic. A brittle material breaks with an increasing stress before the permanent deformation is large. A ductile or tough material under an increasing stress becomes plastic and undergoes a large permanent change of shape. Hence deformations due to straining action are either *elastic* deformations or *plastic* deformations, often termed permanent sets.

According to the best experiments, and especially those of Bauschinger, most materials used in construction, except a few like hard steel, show a small amount of permanent set after loading the first time, even if the loads are comparatively small. But in many materials, and up to a certain limit of stress called the *elastic limit*, the permanent sets are very small, and may perhaps rather be ascribed to initial want of straightness of the bars tested or to small defects of homogeneousness than to any inherent property of the material.

Within the limit of elasticity a very simple relation holds between the stresses or deforming forces and the strains or deformations. This law was published in 1676 by Robert Hooke, in the form of an anagram : ' The true theory of *elasticity* or *springiness*, c e iii n o sss tt uu.' The key to this anagram was given, two years later, in the phrase, ' Ut tensio sic vis ; the power of any spring is in the same proportion with the tension thereof.' Using more modern terms, we say the stress is proportional to the strain. Later it will be shown to what extent actual materials conform to this law and behave with sensibly perfect elasticity. At present it is enough to assume that with most materials, and within the ordinary range of working stress, the plastic or permanent deformations are small enough to be neglected, and the temporary or elastic deformations conform to Hooke's law.

NORMAL STRESS

2. Let a prismatic bar be subjected to an axial pull or thrust P applied at the ends. Apart from local action near the ends, due to the way in which the straining action is applied, there is a simple uniform tension or thrust on cross-sections

normal to the axis and the prism extends in length and diminishes in section, or shortens in length and increases in cross-section (fig. 1).

Bar subjected to Tension.—Let l be the initial length of the bar, $l + e$ the length after straining. Then e is the elongation. If a is the area of a cross-section normal to the axis, the intensity of tensile stress (or simply the *stress*) on the cross section is—

$$p = \text{T}/a \text{ lbs (or tons) per sq. in.}$$

and this is the measure of the molecular actions at the cross-section which resist the straining action.

The *strain* reckoned per unit length or *extension* is—

$$\lambda = e/l \text{ inches per inch.}$$

The total elongation of a bar is in practice usually expressed as a percentage of the initial length, so that the elongation per cent. is—

$$e\,\% = 100\lambda = 100\,e/l.$$

If the material is elastic, by Hooke's law the stresses are proportional to the strains, so that

$$p = \text{E}\lambda \quad \text{and} \quad \lambda = p/\text{E}. \quad . \quad . \quad . \quad (1),$$

where E is a constant for a given elastic material, termed the coefficient of direct elasticity or Young's modulus. The reciprocal of E or $\epsilon = 1/\text{E}$ may be termed the specific extension or extension constant. It is the extension per unit length per unit load. Hence

$$\lambda = \epsilon p.$$

Usually T is given in lbs. (or tons); p in lbs. (or tons) per sq. in.; e in inches; λ in inches per in.; E in lbs. (or tons) per sq. in.

For some imperfectly elastic materials

$$\lambda = a\,p^n$$

where a and n are constants. For cast iron, copper, zinc, stone, and cement $n > 1$, and the extension increases faster than the stress. For leather $n < 1$.

Bar in Compression.—Let l be the initial length of the

bar, p_c the thrust per unit area, and $l - c$ the length after straining. The shortening per unit length or *compression* is—

$$\lambda_c = -c/l,$$
$$p_c = \text{E}\,\lambda_c \quad \text{and} \quad \lambda_c = p_c/\text{E} \quad . \quad . \quad (1a).$$

For metals the value of E is practically the same in tension and compression, if the stress is within the elastic range.

3. *Poisson's Ratio.*—When a bar is extended or compressed by a simple longitudinal stress of the kind described above, it contracts or dilates laterally. If $\pm\,\lambda$ is the longitudinal extension or compression, reckoned per unit of length, then the contraction or dilation transversely is $\mp\,\lambda/m$, where $1/m$,

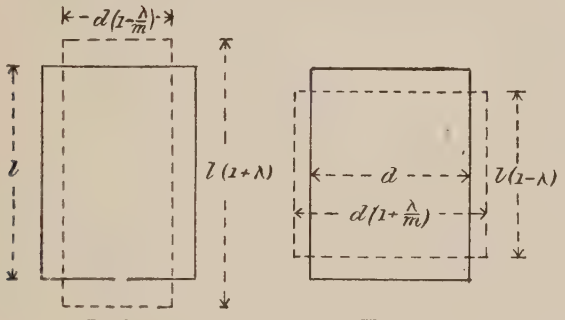


FIG. 1.

the ratio of lateral contraction to longitudinal extension, is a constant termed Poisson's ratio.

For a perfectly incompressible body $m = 2$ and $1/m = 0{\cdot}5$. For india-rubber Poisson's ratio has nearly this value. Generally m is greater than 2, and on the uniconstant theory of elasticity it should have the value 4 for perfectly homogeneous elastic solids. For metals m is rather less than 4, and may be taken at $3\frac{1}{3}$ on the average. For stresses above the elastic limit it falls towards the value 2.

Change of Volume under Simple Direct Stress.—Suppose the prism has initially the length l and cross-section a. Subjected to a longitudinal tension the length becomes $l\,(1 + \lambda)$, and the section $a\,(1 - \lambda/m)^2$. Consequently the initial volume $a\,l$ is changed into $a\,l\,(1 + \lambda - 2\,\lambda/m)$ very nearly, since the deformations are small. The change of unit volume is $\lambda - 2\lambda/m$. Thus, if $m = 4$, as is nearly the case

for elastic metals, the change of volume of one cubic unit is $\lambda/2$, the volume being increased by a longitudinal tension and decreased by a longitudinal compression. If $m = 2$ as for india-rubber, or metals in the plastic stage, there is no change of volume.

4. *Work done in Extending or Compressing an Elastic Bar.*—If the stress is gradually increased from zero to p, the mean stress is $p/2$ per unit area, and the elongation (or compression) per unit length is λ. Hence the work per unit volume of the bar is—

$$u = \frac{1}{2} p \lambda = \frac{1}{2} \epsilon p^2 \text{ inch-lbs. (or tons).}$$

In the case of bars strained beyond the elastic limit which extend plastically to a great extent, if ϵ is the total extension (or compression) per unit length and p the stress per unit area, the work done may reach 0·7 to 0·8 ϵp^2 inch-lbs. (or tons) per unit volume.

5. *Numerical Values of the Constants.*—In order to have some idea of the numerical importance of the quantities which are under discussion, it is desirable to examine a few cases. The following are values of the modulus E in tons per sq. in., and the extension and work of extension for each ton per sq. in. for some materials, the straining action being within the elastic limit :—

Material.	Coefficient of elasticity E Tons per sq. in.	Extension constant ϵ Extension per ton per sq. in. per inch length in inches.	Work of extension per ton per sq. in. per cubic in. in inch-tons.	Poisson's Ratio $\frac{1}{m}$
Wrought Iron	12,500	·000080	·000040	·28
Mild Steel . .	13,800	·000072	·000036	·29
Cast Iron . {	6,250	·000160	·000080	—
{	10,020	·000099	·000050	—
Glass . . .	3,530	·00028	·000140	·25
Bronze . . .	4,400	·00023	·000115	·30
Yellow Deal .	715	·0014	·0007	—

Taking ordinary steel, such as used in riveted work, the elastic limit will not be below 10 tons per sq. in. Up to that stress the extension will be 0·0007, or about $\frac{1}{1400}$th of its initial length. Hence the lateral contraction will be about $\frac{1}{3500}$th of its initial width. The increase of volume when

stretched will be about $\frac{1}{2800}$th. The work in stretching the bar up to 10 tons per sq. in. will be $0{\cdot}5 \times 10 \times 0{\cdot}0007 = 0{\cdot}0035$ in.-tons per cubic in. of volume of the bar.

6. *Tension and Compression when the Limit of Elasticity is Exceeded.*—For imperfectly elastic bodies or for straining actions beyond the range of elasticity, the strains increase faster than the stresses, and a great part of the deformation is plastic deformation or permanent set. Some bodies loaded beyond the elastic limit, unloaded and reloaded, are found to have acquired a new elastic limit higher than the original elastic limit. This variation of the position of the elastic limit will be discussed later.

7. *Elastic Afterworking or Elastic Lag.*—In some materials time is required before the full deformation due to a straining action is developed. Similarly, when the straining action is removed, the return to the primitive condition is gradual and only completed after an interval of time.

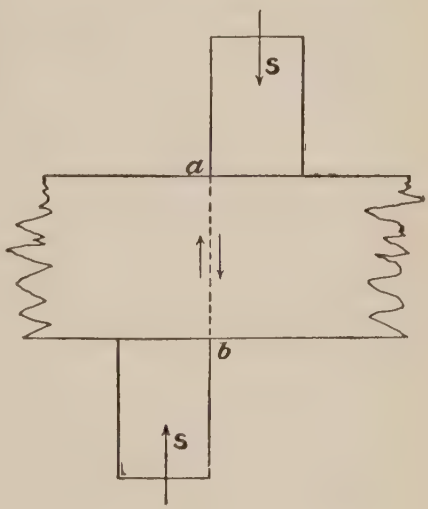


FIG. 2.

The phenomenon is analogous to magnetic hysteresis and is due to internal friction of the molecules.

SHEARING STRESS

8. Let a straining action be applied as shown in fig. 2. The bar tends to shear in the plane $a\,b$. If s is the whole force applied and a the area of the section, the tangential or shearing stress is $s = \mathrm{s}/a$. If the force is not applied exactly in one plane, and any bending occurs, the average stress is s, but the stress is not uniform on the section.

In general, in a solid, shearing on a set of parallel planes is accompanied by shearing on another set of parallel planes. In one case the whole condition of stress can be reduced to

shearing stress on planes at right angles, and the body is then said to be subjected to simple shearing stress.

Consider a case in which the stress can be reduced to simple shearing stress. Let the rectangle A B C D represent a parallelopiped, the stresses on which can be reduced to tangential stresses of intensities, p_1, p_2, on two pairs of the faces. Then it can be shown that the stresses on the faces at right angles are equal. For the lengths of the sides represent the areas of the faces, so that the total stresses on the faces are $p_2 \times$ A B and $p_1 \times$ A D. Equating the moments of the two couples, $p_2 \times$ A B $\times$ B C $= p_1 \times$ A D $\times$ A B, that is, $p_2 = p_1$.

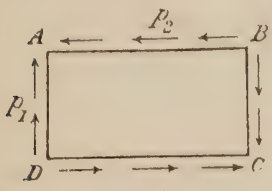


FIG. 3.

Let a cube of material (fig. 4) be subjected to equal shearing stresses of intensity s on two pairs of opposite faces. If a is the area of one face $s = sa$ is the total stress on each face, and the resultant stresses form the equal pair of couples s, — s, and s, — s, a system of forces in equilibrium. The cube is distorted into an oblique prism without change of volume. The distortion may be measured by the relative displacement $a\,a'$ of two opposite faces. The displacement $\sigma = a\,a'/a\,o$ of two faces at unit distance is termed the *sliding*. By Hooke's law $s = c\,\sigma$, where c is a coefficient of elasticity termed the *coefficient of rigidity* or coefficient of resistance to change of shape.

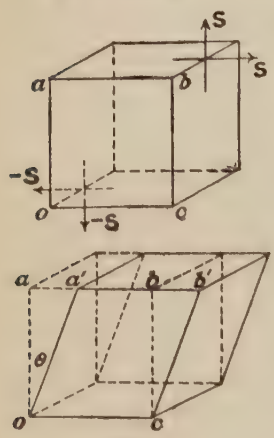


FIG. 4.

Each right angle $a\,o\,c$ is altered by an amount $a\,o\,a' = \theta$ in circular measure. But since the deformation is small

$$\theta = \tan\theta = a\,a'/a\,o = \sigma,$$

and

$$s = c\theta = c\sigma \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Clearly the material is lengthened in the direction $o\,b$ and shortened in the direction $a'\,c$. Let fig. 5 represent a face of the cube distorted by shearing into the rhombus $o\,a'\,b'\,c$.

The extension per unit length in the direction $o\,b'$ is $\lambda = (o\,b' - o\,b)/o\,b$. From o describe the arc $b'\,g$. Then

$$\lambda = b\,g/o\,b = b\,b'\cos\phi/c\,b\,\operatorname{cosec}\phi = \frac{1}{2}\frac{b\,b'}{c\,b}\sin 2\phi.$$

But since $\phi = 45°$,

$$\lambda = \frac{1}{2}\frac{b\,b'}{c\,b} = \frac{1}{2}\frac{a\,a'}{a\,o} = \frac{\theta}{2} = \frac{\sigma}{2}.$$

Similarly the shortening along $a'\,c$ is $-\frac{1}{2}\theta = -\frac{1}{2}\sigma$. That is, the extension and compression along the diagonals of the face of a cube subjected to shearing are each half the sliding. Hence—

$$s = 2\,c\,\lambda$$

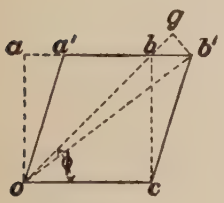


Fig. 5.

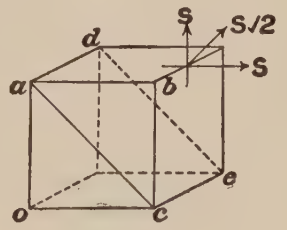


Fig. 6.

Consider the diagonal plane $a\,d\,e\,c$ (fig. 6), the area of which is $a\sqrt{2}$, if a is the area of a face of the cube. The forces s, s, to the right of this plane have a resultant $s\sqrt{2}$ normal to $a\,d\,e\,c$. Hence there is on this plane a simple tension of intensity.

$$p_t = (s\sqrt{2})/(a\sqrt{2}) = s/a = s,$$

that is equal to the shearing stress on the faces of the cube. Similarly, on the diagonal plane at right angles to $a\,d\,e\,c$ there is a simple compressive stress of intensity, $p_c = s$. Consequently a simple shearing stress is equivalent to a tension and compression, of the same intensity as the shearing stress, on a pair of planes inclined at 45° to the planes on which the stress is wholly a shearing stress.

9. *Superposition of Two Simple Direct Stresses at Right Angles.*—Consider a small cube, of unit length of side, with simple stresses normal to two pairs of faces and parallel to

the third pair (fig. 7). Under the action of p_1 there will be the following strains:

parallel to O C, p_1/E,

parallel to O B and O A, $-p_1/m\,E$.

Under the action of p_2 the strains are—

parallel to O B, p_2/E;

parallel to O A and O C, $-p_2/m\,E$.

Adding the parallel strains—

$$\text{parallel to O C,}\quad \lambda_1 = \frac{p_1}{E} - \frac{p_2}{m\,E},$$

$$\text{O B,}\quad \lambda_2 = \frac{p_2}{E} - \frac{p_1}{m\,E},$$

$$\text{O A,}\quad \lambda_3 = -\frac{p_1}{m\,E} - \frac{p_2}{m\,E}.$$

Now let the stresses p_1, p_2 be of equal intensity, p, but opposite sign. The condition is that of a simple shearing stress, and the strains are—

$$\frac{p}{E}\left(1+\frac{1}{m}\right);\ -\frac{p}{E}\left(1+\frac{1}{m}\right) \text{ and } 0 \quad . \quad (3),$$

or putting

$$\frac{p}{E}\left(1+\frac{1}{m}\right) = \lambda,$$

the length of the sides of the cube will be

$$1+\lambda;\ 1-\lambda; \text{ and } 1 \quad . \quad . \quad . \quad (4),$$

and neglecting λ^2 the volume is unchanged. Fig. 8 shows the distorted cube.

10. *Relations of the Coefficients* c *and* E.—In the case of a simple shearing stress, the relation of stress and strain is—

$$s = c\,\theta = c\,\sigma = 2\,c\,\lambda.$$

Also, since the shearing stress is equivalent to a thrust and

tension at right angles of intensity equal to s, producing an extension and compression—

$$\lambda = \frac{p}{\text{E}}\left(1 + \frac{1}{m}\right)$$

and

$$p = s = 2\,\text{c}\,\lambda,$$

$$\text{E} = \frac{2\text{c}\,(m+1)}{m} \quad . \quad . \quad . \quad . \quad (5).$$

For $m = 4$, $\text{c} = \frac{2}{5}\,\text{E}$. Taking the more usual value $m = 3\frac{1}{3}$, $\text{c} = 0{\cdot}385\,\text{E}$.

11. *Isotropy.*—A material may, when tested by direct tension for instance, give one value of E for a stress in one direction and a different value of E for a

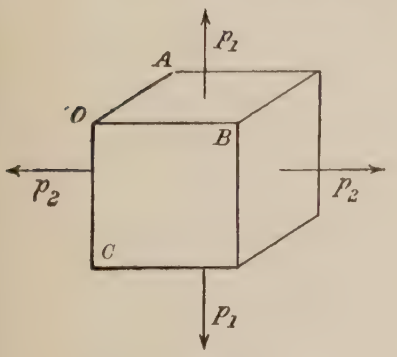


Fig. 7.

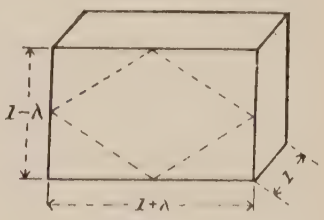


Fig. 8.

stress in another direction. The materials used in construction are produced by processes of forging, rolling, &c., in which the mechanical actions have definite directions with reference to the piece produced. The pressure of the rolls on a bar is perpendicular to its axis, and while the bar is squeezed down vertically it has different degrees of freedom of expansion in all horizontal directions. It is quite conceivable that this mechanical action should make the elastic properties, in the direction in which the bar was compressed, different from those in the direction in which it expanded. The bar would then be said to be not isotropic.

Now, fortunately, most of the mechanical operations in producing iron and steel are effected at temperatures at which the material is almost perfectly plastic, and they do not produce such great differences in the elastic properties in different directions as similar operations at lower temperatures

would do. We may for most purposes treat ordinary materials as isotropic, always remembering that the assumption is approximate. The extent to which there are variations of isotropy in ordinary materials has hardly been experimentally examined.

12. *Normal and Tangential Components of Stress.*— Suppose a simple stress, P, applied parallel to the axis of a bar, so that the distribution on cross-sections perpendicular to the axis is uniform. If a is the area of such a cross-section the intensity of stress is—

$$p = P/a \quad . \quad . \quad . \quad . \quad (6).$$

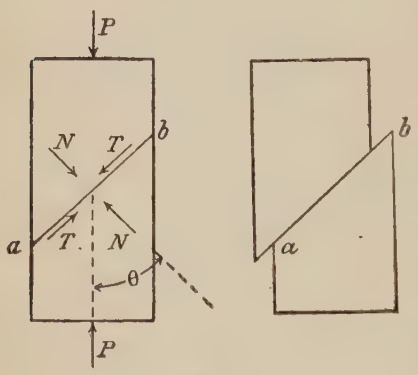


FIG. 9.

To find the stresses on an oblique section, $a\ b$, it is convenient to resolve P into normal and tangential components. Let θ be the angle between the normal to the section and the axis of the bar, then $N = P \cos \theta$ and $T = P \sin \theta$. As the tangential stress T tends to cause sliding at the section, it is called the shearing stress, while the normal component is often termed the direct stress. The area of the oblique section $a\ b$ is $a \sec \theta$. Hence the intensities of normal and tangential stress on $a\ b$ are—

$$\text{Normal stress} = p_n = \frac{P \cos \theta}{a \sec \theta} = p \cos^2 \theta \quad . \quad . \quad . \quad (7).$$

$$\text{Tangential stress} = p_t = \frac{P \sin \theta}{a \sec \theta} = p \sin \theta \cos \theta \quad . \quad . \quad (8).$$

For an oblique section at right angles to $a\ b$, substituting $\frac{\pi}{2} - \theta$ for θ, we get—

$$\text{Normal stress} = p'_n = p \sin^2 \theta.$$
$$\text{Tangential stress} = p'_t = p \sin \theta \cos \theta.$$

So that the intensity of tangential stress is the same on two oblique sections at right angles. The shearing stress is greatest, and $= \frac{1}{2}p$ for planes at 45° with the axis.

13. *Coefficient of Elasticity of Volume.*—When a body is acted on by a stress uniform all round, like a fluid pressure, its volume is increased or diminished. Let v be the change of volume reckoned per cubic unit of the body under a stress, p, per sq. unit of area. Then—

$$\text{K} = p/v \quad . \quad . \quad . \quad . \quad (9)$$

is called the coefficient of elasticity of volume. All systems of stress acting on a body may be resolved into distorting or shearing stresses, which do not alter the volume, and a fluid stress.

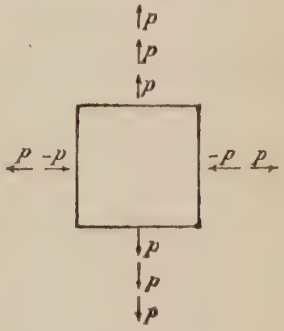


Fig. 10.

The relation between K and the other constants is easily found. For suppose a cube of unit length of side acted on by a longitudinal stress, $3p$, on two opposite faces. It will in no way alter the condition of stress to introduce stresses, $+p$ and $-p$, on each of the remaining four faces. Considering the stress shown in the figure, $+p$ on each horizontal face and $-p$ on opposite vertical faces together form a shearing or distorting stress; similarly, $+p$ on each horizontal face and $-p$ on the two other vertical faces. These produce no change of volume. There remains, therefore, a stress $+p$ on every face, together constituting a fluid stress of intensity, p.

But it has already been shown that a longitudinal stress, $3p$, would produce a change of volume equal to $3\ (\lambda - 2\lambda/m)$. Therefore, discarding the distorting stresses, which produce no change of volume, a longitudinal stress, $3p$, produces the same change of volume as a fluid stress, p. Hence—

$$\text{K} = \frac{p}{3(\lambda - 2\lambda/m)} \quad . \quad . \quad . \quad (10).$$

Remembering that $\lambda = p/\text{E}$ and also the equation between

C and E already found, we can put the relation of the constants E, C, K, and m in the following forms:

$$K = \frac{E\,m}{3m-6} = \frac{2C(m+1)}{3m-6}$$

$$= \frac{C\,E}{9C-3E},$$

$$E = \frac{2C(m+1)}{m}$$

$$= \frac{9C\,K}{3K+C},$$

$$C = \frac{E\,m}{2(m+1)} = \frac{K(3m-6)}{2(m+1)},$$

$$m = \frac{6K+2C}{3K-2C} = \frac{2C}{E-2C}.$$

If $m = 4$, then $K = \frac{2}{3}E = \frac{5}{3}C$; $E = \frac{5}{2}C$; $C = \frac{2}{5}E = \frac{3}{5}K$.

According to the view generally adopted in this country C and K may be regarded as fundamental coefficients in the theory of elasticity of isotropic bodies.

14. *Examples of the Value of Constants.*—The following short table gives values of the constants discussed above in tons per square inch:

COEFFICIENTS OF ELASTICITY

—	Volume elasticity K	Rigidity C	Young's modulus E	Poisson's ratio 1/m	m
Water . .	143	—	—	—	—
Mercury .	3,510	—	—	—	—
Glass (flint) .	2,204–2,636	1,492–1,524	3,645–3,829	·244	4·1
Brass . .	6,363–6,890	2,185–2,560	6,020–7,112	·333	3·0
Copper . .	10,690	2,794–3,440	7,442–7,836	·333	3·0
Cast iron .	6,123	3,378	6,250–10,220	·270	3·7
Wrought iron	9,245	4,883	12,470	·278	3·6
Steel .	11,690	5,200	12,820–15,560	·303	3·3

TORSION

15. When a prismatic bar is fixed at one end and a couple is applied at the other end, in a plane at right angles to the axis of the bar, it suffers a deformation termed torsion, which gives rise to simple shearing stresses. It is sufficient for testing purposes to consider a cylindrical bar, the theory of which is simple. Torsion tests are a convenient means of determining the coefficient of rigidity, c.

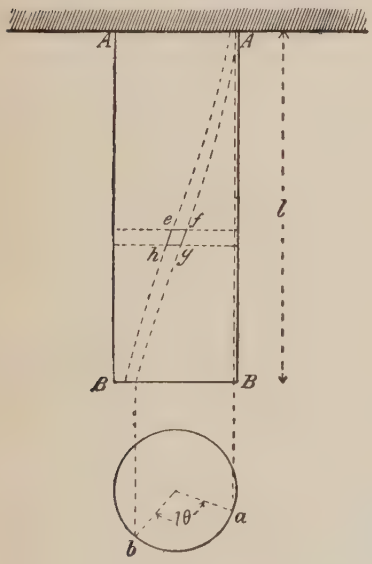


FIG. 11.

In such a bar A A, B B (fig. 11) each plane transverse section remains plane after twisting, and its dimensions are unaltered. The distance

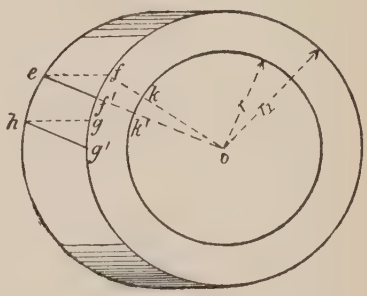


FIG. 12.

between two transverse sections is unchanged, so that the length of the bar is unaltered. A longitudinal strip on the surface of the bar initially parallel to the axis becomes a helix in the twisted bar. Any small square on the surface of the bar becomes a rhombus, $efgh$. This deformation corresponds to that produced by equal shearing forces on the opposite sides of the square $efgh$, or to stresses of tension, and compression of equal intensity with the shearing stresses along the diagonals of $efgh$—that is, at 45° with the axis of the bar.

Hence the general condition of stress in the bar is that there are shearing stresses on traverse sections and on radial longitudinal sections. Or, there are tensions and compressions along helixes drawn on concentric cylindrical sections at an inclination of 45° with the axis.

Let θ be the angle through which the bar is twisted, per unit of length, expressed in circular measure. That is, if $a\,b$ is the arc through which a point on the surface of the bar at the radius r_1 turns, then—

$$\theta = a\,b/r_1\,l.$$

[If n is the torsion angle per unit length of bar in degrees, $\theta = \pi\,n/180$.]

Consider the slice between transverse sections at a distance $d\,l$ (fig. 12). One twists relatively to the other through an angle $f\,o\,f' = \theta\,d\,l$. A square, $e\,f\,g\,h$, on the surface of the slice becomes a rhombus, $e\,f'\,g'\,h$. Now the arc $f\,f' = r_1\,\theta\,d\,l$. For any intermediate cylindrical section of the slice at radius r, the corresponding deformation is $k\,k' = r\,\theta\,d\,l$. The angle of deformation of the rhombus on the surface of the bar is $f\,f'/e\,f = \phi_1 = r_1\,\theta$; and the corresponding angle of deformation of a rhombus on the cylinder of a radius r is $\phi = r\,\theta$.

Now consider the stress on a ring between radii r and $r + d\,r$ at the end of the slice. The area of the ring is $2\,\pi\,r\,d\,r$. If f is the stress per unit of area, the whole stress on the ring is $2\,\pi\,f\,r\,d\,r$, and the moment of this stress about the axis of the bar is $2\,\pi\,f\,r^2\,d\,r$. Hence the whole moment of stress on the end of the bar, which must be equal to the external twisting moment, must be—

$$\mathrm{T} = 2\pi \int f\,r^2\,d\,r.$$

But in shearing, the relation of stress and strain gives, at the surface of the bar,

$$f_1 = \mathrm{c}\,\phi_1 = \mathrm{c}\,r_1\,\theta,$$

and at radius r,

$$f = \mathrm{c}\,\phi = \mathrm{c}\,r\,\theta.$$

Hence—

$$\left.\begin{aligned} \mathrm{T} &= 2\pi\,\mathrm{c}\,\theta \int r^3\,d\,r \\ &= \tfrac{1}{2}\pi\,\mathrm{c}\,\theta\,r_1^4 \end{aligned}\right\}. \quad . \quad . \quad . \quad (11).$$

Or, putting in f_1 the shearing stress at the surface of the bar,

$$\mathrm{T} = \tfrac{1}{2}\pi\,f_1\,r_1^3 \quad . \quad . \quad . \quad . \quad (12).$$

When the section of the bar is not circular, the determination of the relation of the moment of torsion, greatest stress, and angle of twist is difficult. The greatest stress is, in the cases most

likely to occur, at those points of the boundary of the section which are nearest the centre. The following are the equations obtained by St. Venant:

Let A be the area of the section.

J the polar moment of inertia of the section relatively to its centre of gravity.

J′ the moment of inertia relatively to an axis through the centre of gravity, and coinciding with its greater diameter.

a, b, the greater and less semi-diameters if the section is elliptical, the greater and less half-lengths of the sides if rectangular.

f_1 the greatest stress.

Then

$$\theta = k \frac{T}{C} \frac{J}{A^4} \quad . \quad . \quad . \quad . \quad (13),$$

$$f_1 = \gamma \frac{T}{J} b \quad . \quad . \quad . \quad . \quad (14),$$

where

$k = 4\pi^2$ for elliptical sections,
$= 40$ approximately for rectangular sections;
$\gamma = 0{\cdot}5$ for elliptical sections,
$= 0{\cdot}75$ for rectangular sections.

It may be pointed out that experiments on torsion, in which the stresses are within the elastic limit, afford the easiest means of determining the coefficient of transverse elasticity C.

16. *Determination of* C *by Torsional Vibrations.*—When the value of C is required for thin cylindrical bars or wires the method of torsional vibrations may be used. It can be shown that torsional vibrations of a wire fixed above and supporting a weight are nearly isochronous, and that the time of a single oscillation is given by the relation

$$t = \pi \sqrt{\frac{J}{T}},$$

where t is the time in seconds, J the moment of inertia of the vibration system about its axis of rotation, and T the twisting couple when $l\theta = 1$. Hence, since—

$$T = \frac{\pi}{2} C \frac{r^4}{l},$$

$$C = \frac{2\pi J l}{t^2 r^4} \quad . \quad . \quad . \quad . \quad (15).$$

BENDING

17. A bar is subjected to simple plane bending when the following conditions are satisfied: (1) The unstrained bar is straight, and has a longitudinal plane of symmetry; (2) the bending forces are applied in that plane normally to the axis. These conditions are easy to obtain, and the deformation which occurs is one of the easiest to observe. Hence materials are often tested by bending.

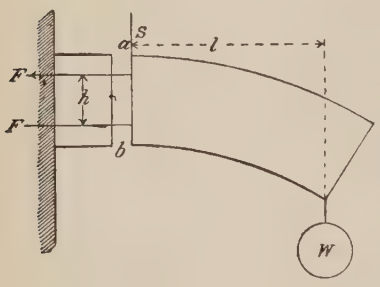


Fig. 13.

The nature of the stresses to which the bending forces give rise is not difficult to trace. Suppose a prismatic bar (fig. 13), fixed at one end and loaded with w at the other. If the bar were divided at $a\,b$, equilibrium might be re-established by introducing a vertical force, s, equal to w, and a pair of equal horizontal forces, F,—F, forming a tension and thrust, and having a moment F h equal and opposite to the moment w l of the couple formed by w and s.

This illustration serves to show that at a cross-section of a bent bar, normal to the axis, the molecular forces must in general consist of a shearing stress corresponding to s, and of direct stresses of tension and compression having resultants corresponding to F F.

The existence of these direct tensions and compressions at the upper and lower edges of the bar is easily shown, thus:

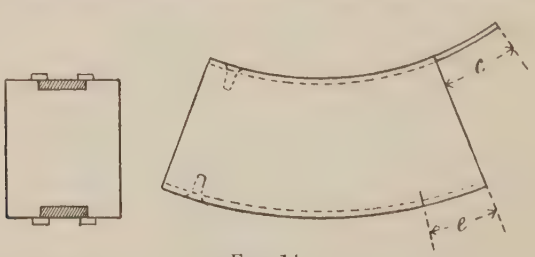


Fig. 14.

Suppose a rectangular bar of wood to have thin pieces of steel fitted in grooves in its top and bottom surfaces. Let

these be fixed to the bar at one end, but otherwise free to slide longitudinally. If the bar is now bent it will be found that the bar has shortened a distance c on one side and lengthened a distance e on the other, as shown by the projection or retraction of the thin steel plates. Further, the compression c will be equal to the extension e if the bar is symmetrical above and below its axis. These observations suggest a conception of bending which is accurate enough for most practical purposes.

Since the bar is lengthened on one side and shortened

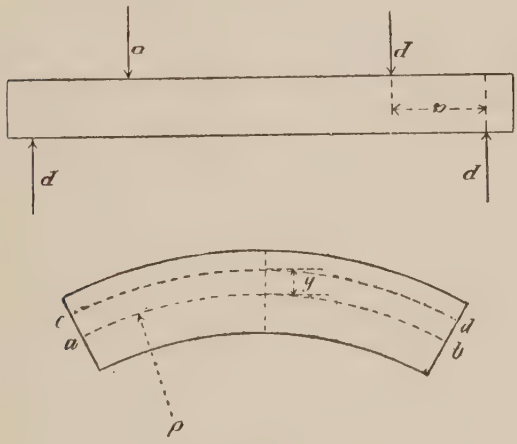


Fig. 15.

on the other, at some intermediate surface, termed the neutral surface, the material is neither lengthened nor shortened. Further, for other parts of the material, the elongation or shortening (parallel to the longitudinal axis) will be proportional to the distance from the neutral surface. The stresses will therefore also be proportional to that distance.

Generally, as has been shown, there is a shearing force at the transverse sections of the bar, and the moment of the bending forces varies along the bar. In one particular case the action is simpler (fig. 15). Suppose equal couples of moment $P\,a$ applied at the ends of the bar, then between A and B the bending moment is uniform and the curvature circular. Let ρ be the radius of curvature measured to the

neutral surface $a\,b$. Then a fibre of the length $a\,b$ before curvature has the length $c\,d$ after bending. But

$$\frac{c\,d}{a\,b} = \frac{2\pi(\rho + y)}{2\pi\rho} = \frac{\rho + y}{\rho},$$

and the extension (or compression, if y is negative) is y/ρ per unit of length.

Hence, if f is a stress at a distance y from the neutral surface,

$$f = \text{E}\frac{y}{\rho} \quad . \quad . \quad . \quad . \quad . \quad (16).$$

On an element of area a the stress is $f\,a$, and the total stress on the whole section of the bar is, therefore,

$$\Sigma(f\,a) = \Sigma(\text{E}\frac{y}{\rho}\,a).$$

But, since the pressures and tensions across the section form a couple,

$$\Sigma(\text{E}\frac{y}{\rho}\,a) = 0\,;$$

or, since E/ρ is constant, $\Sigma\,y\,a = 0$.

This equation is only true if the distances y are measured from a line passing through the centre of gravity of the section. Hence the neutral surface of the bar passes through its longitudinal axis of figure.

The moment of the stress $f\,a$ about the neutral axis of the section (intersection of neutral surface with the section) is $f\,a\,y = (\text{E}\,y^2\,a)\,\rho$. The total moment of the couple formed by the tensions and pressures at the section is—

$$\Sigma\left(\frac{\text{E}\,y^2\,a}{\rho}\right), \text{ or } \frac{\text{E}}{\rho}\,\Sigma\,a\,y^2 \quad . \quad . \quad (17).$$

Now, the quantity $\Sigma\,a\,y^2$ is known as the moment of inertia, or second moment of the section, and is usually denoted by I. Hence, putting M for the moment of the forces on one side of the section, which is equal to the moment of the molecular forces at the section—

$$\text{M} = \frac{\text{E}\,\text{I}}{\rho} \quad . \quad . \quad . \quad . \quad (18),$$

which expresses the relation between the bending moment and the curvature of the bar. Let f_t and f_c be the tension and pressure at distances y_t and y_c from the neutral surface. Then—

$$f_t = \frac{E}{\rho} y_t, \quad f_c = \frac{E}{\rho} y_c,$$

$$M = f_t \frac{J}{y_t} = f_c \frac{J}{y_c} \quad . \quad . \quad . \quad . \quad (19).$$

Generally it is necessary to consider the greatest tension

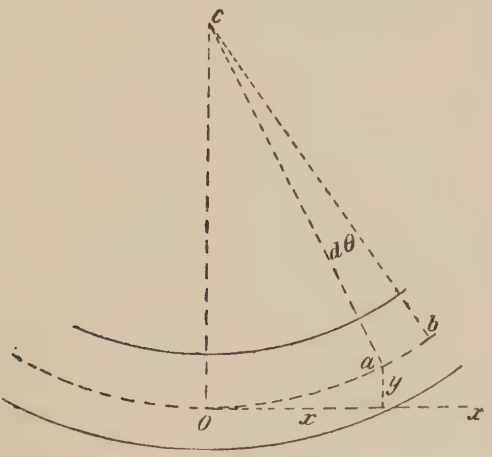


Fig. 16.

and pressure at any point of the cross-section. Then y_t and y_c must be taken as the distances of the parts of the section furthest from its neutral axis. It is convenient to call the quantities J/y_t, J/y_c the moduli of the section for tension and compression. If Z_t, Z_c are put for these moduli,

$$M = f Z = f_c Z_c \quad . \quad . \quad . \quad (20),$$

which gives the relation of the bending moment to the stresses induced.

If the bending moment varies along the beam the radius of curvature ρ also varies. Then eq. 18 gives ρ for the section at which the bending moment is M. If J varies, then eq. 18 gives different values of M or f at different sections.

18. *Deflection of a Beam.*—Let a be a point on the neutral

axis, and b a neighbouring point (fig. 16); let x and y be co-ordinates of a, c the centre of curvature, and $a\,c = \rho$. Then $a\,c\,b = d\,\theta$ is equal to the angle between the tangents to the neutral surface at a and b, or the increment of slope of the beam. Let $a\,b = d\,s = \rho\,d\,\theta$, and, since $d\,s = d\,x$ very nearly,

$$\frac{d\,\theta}{d\,x} = \frac{1}{\rho},$$

$$\theta = \frac{d\,x}{\rho} = \int \frac{\text{M}}{\text{E J}}\,d\,x \quad . \quad . \quad (21),$$

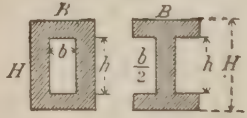
which can be integrated when M and J are expressed in terms of x.

Further, if the deflection of b below $a = y$, $d^2\,y \div d\,x = \theta$,

$$y = \int \theta\,d\,x \, . \quad . \quad . \quad . \quad (22),$$

which again is integrable.

19. *Application to the Simplest Cases occurring in Testing.*—The values of J and z for the simplest forms of section are as follows:

	Area, A	Moment of inertia, J	Modulus of section, Z
	$b\,h$	$\frac{1}{12}\,b\,h^3$	$\frac{1}{6}\,b\,h^2$
	s^2	$\frac{1}{12}\,s^4$	$\frac{1}{6}\,s^3$
	$\frac{\pi}{4}\,d^2$	$\frac{\pi}{64}\,d^4$	$\frac{\pi}{32}\,d^3$ $= .0982\,d^3$
 Hollow rectangle, or I, with equal flanges	$\text{B H} - b\,h$	$\frac{\text{B H}^3 - b\,h^3}{12}$	$\frac{\text{B H}^3 - b\,h^3}{6\,\text{H}}$

For irregular sections, such as rail sections, the area and moment of inertia must be determined by well-known graphic methods. But the following approximation is suitable for ordinary rails. Let A be the area of section, h the height of the rail. Then—

$$J = 0{\cdot}126\ A\ h^2,$$
$$z = 0{\cdot}2525\ A\ h.$$

The greatest bending moment for the simplest modes of loading is as follows:

I. Beams encastré at one end, length l.

Load W at the free end l from support—
M at support = $W\ l$.
Load w per unit of length uniformly distributed—
M at support = $\frac{1}{2}\ w\ l^2$.

II. Beams supported at each end, span l.

Load W in centre—
M at centre = $\frac{1}{4}\ W\ l$.
Load w per unit of length uniformly distributed—
M at centre = $\frac{1}{8}\ w\ l^2$.

The greatest longitudinal tension or compression for a given bending moment and section is—

Rectangular section $f = \dfrac{6\ M}{b\ h^2}$.

Circular section $f = \dfrac{10{\cdot}2\ M}{d^3}$.

I section $f = \dfrac{6\ H\ M}{B\ H^3 - b\ h^3}$.

The greatest deflection δ is as follows for beams of uniform section:

I. Beam encastré at one end, length l.

Loaded at free end with W—

$$\delta = \frac{1}{3}\ \frac{W\ l^3}{E\ J}$$ at the free end.

Loaded uniformly with w per unit of length—

$$\delta = \frac{1}{8}\ \frac{w\ l^3}{E\ J}$$ at the free end.

II. Beam supported at each end, span l.

Loaded at the centre with W—

$$\delta = \frac{w\,l^3}{48\,E\,J} \text{ at centre.}$$

Uniformly loaded with w per unit of length—

$$\delta = \frac{5\,w\,l^4}{384\,E\,J} \text{ at centre.}$$

If there is a concentrated and distributed load, the deflections due to each may be added.

20. *Determination of Young's Modulus by Experiments on Bending.*—If a uniform prismatic bar is encastré at one end and loaded at the other with a weight W, and the deflection δ is measured,

$$E = \frac{1\,W\,l^3}{3\,\delta\,J} \quad . \quad . \quad . \quad . \quad (23).$$

Similarly, if a prismatic beam of uniform section is supported at the ends and loaded at the centre with W,

$$E = \frac{W\,l^3}{48\,\delta\,J} \quad . \quad . \quad . \quad . \quad (24).$$

It is assumed, of course, that the stresses do not exceed the elastic limit, and that the observations are repeated often enough and the measurements sufficiently delicate to give trustworthy values of the deflection.

21. *Bending when the Elastic Limit is exceeded.*— In the theory of the bending of an elastic bar, it is assumed that the elementary fibres, of which the bar may be imagined to be made up, act as independent fibres. Any section plane and normal to the axis before bending is assumed to be plane and normal to the axis after bending. Lastly, the stresses are assumed proportional to the strains, so that since the strains vary as the distance from the neutral plane, the stresses also vary in the same way—that is, the stress on a cross-section of the bar is a uniformly varying stress. None of these conditions are exactly satisfied if the elastic limit is exceeded.

Suppose a bar broken by bending, and for simplicity suppose that (as is the case with cast iron) it breaks by tension. If the equation $M = f\,Z$ is used, as for an elastic

material, a value is found for the stress f at the edge in tension which should agree with the tensile resistance of the material, if the formula could be rightly used. But, in fact, the value of f so calculated is found to differ from the tenacity found by a tension experiment more or less considerably. The difference varies with the form of the section and is greatest for those sections in which there is most material near the neutral axis. It is least for **I** sections, where most of the material is in the flanges. That such a difference should be found is not surprising, for the stress calculated from the transverse breaking load has been deduced by a formula, strictly true only for elastic bodies, applied in a case in which the elastic limit has been much exceeded. It is, nevertheless, interesting to see how the divergence arises.

Of the suppositions involved in the theory of elastic

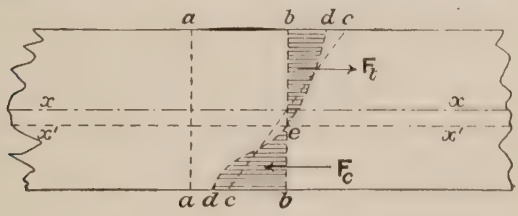


Fig. 17

bending, the assumption that plane sections remain plane appears to be approximately true even when the elastic limit is exceeded. But beyond the elastic limit the stresses do not increase so fast as the strains. Hence, if plane sections remain plane, the stress at a cross-section cannot be a uniformly varying stress, and if the relation of stress and strain are different for tension and compression, then the neutral axis may move away from the axis through the centre of gravity of the section.

Let $a\,a$, $b\,b$ (fig. 17) be part of a beam before bending between two parallel sections, and let $a\,a$, $c\,c$ be the same part after bending, limited by sections plane but not parallel. The horizontal intercepts between $b\,b$ and $c\,c$ will be the strains. Now, if the stresses increase less fast than the strains, the stresses will be given by the horizontal intercepts between $b\,b$, and some curved line such as $d\,e\,d$. If the relation of stress and strain is different for tension and compression, the neutral surface originally at $x\,x$ may have a

new position $x'x'$. The total tension above and compression below the neutral axis, F_t and F_c, will still be equal and form a couple. F_t will be proportional to the area $b\,e\,d$, and will act through the centre of that area. Similarly, F_c will be proportional to $b\,e\,d$, and act through the centre of that area. If the law of variation of stress and strain beyond the elastic limit were known, the curve $d\,e\,d$ could be drawn, and there would be data for determining the real stresses at the edges of the beam—that is, $b\,d$ and $b\,d$—one of which obviously will be less than that calculated on the assumption that the stress is a uniformly varying one. For instance, Hodgkinson found that the relation of stress and strain for cast iron could be expressed by a cubic parabola, the parabola for tension being different from that for compression. Apart from the complexity of introducing this result into expressions for bending strength, it is not clear that in the bent beam the relation of stress and strain would be the same as for bars in simple tension and compression. The mutual action of the fibres may alter the relation of stress and strain when the bar is bent so far that the elastic limit is exceeded.

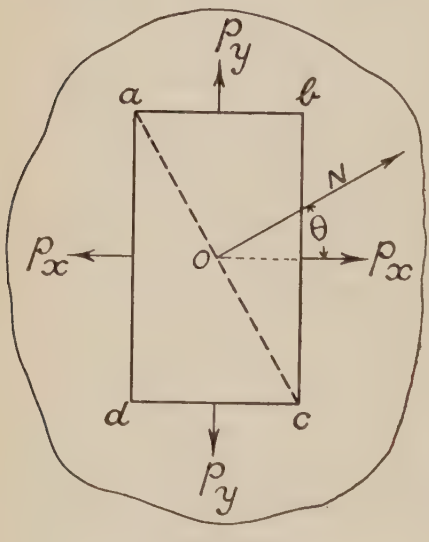


FIG. 18.

COMPOUND STRESS

22. Whatever the condition of stress in a solid in which there are normal and shearing stresses on different planes, there are three planes mutually at right angles on which the stress is wholly a normal stress and these planes are termed principal planes and the stresses on them principal stresses.

In many cases in practice there is no stress on one of

these planes or one of the principal stresses is zero. The state of stress is then said to be two dimensional.

Given a pair of principal stresses on two planes at right angles to find the stress on any third plane. Let the principal stresses p_x, p_y act in the plane of the paper (fig. 18), and let $a\,c$ normal to the plane of the paper be the plane on which the stress is required. Let O N be the normal to $a\,c$ making an angle θ with the direction of p_x. Conceive a parallelopiped of which $a\,c$ is the diagonal plane, of unit thickness normal to the paper. On $a\,b$, $b\,c$ the total normal stresses are $P_x = p_x \times b\,c$ and $P_y = p_y \times a\,b$. Let p_n and p_t be the normal and tangential stresses on $a\,c$. Tensions are reckoned positive and compressions negative.

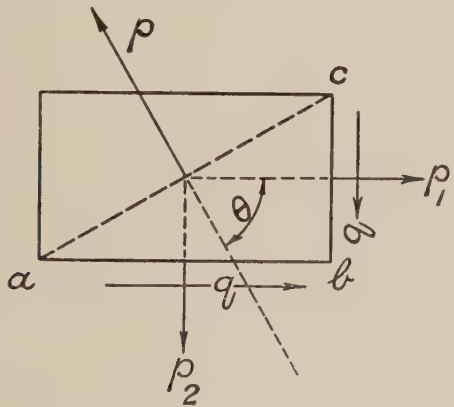


FIG. 19.

Resolving in the direction O N,

$$p_n \times a\,c = p_x \times b\,c \cos\theta + p_y \times a\,b \sin\theta,$$

$$p_n = p_x \cos^2\theta + p_y \sin^2\theta \quad . \quad . \quad . \quad (25).$$

Similarly resolving in the direction $a\,c$,

$$p_t \times a\,c = p_x \times b\,c \sin\theta - p_y \times a\,b \cos\theta,$$

$$p_t = (p_x - p_y) \sin\theta \cos\theta$$

$$= \tfrac{1}{2}(p_x - p_y) \sin 2\theta \quad . \quad . \quad . \quad (26).$$

If $\theta = 45°$, $p_t = \frac{1}{2}(p_x - p_y)$ and this is the greatest shearing stress on any plane. The normal stress on this plane is

$$p_n = \tfrac{1}{2}(p_x + p_y).$$

Given normal and shearing stresses on two planes at right angles to find the principal stresses. Let p_1, p_2 be the stresses in the plane of the paper (fig. 19) normal to $c\,b$, $b\,a$ (tensions being +, compressions −), and q the shearing stresses, which on planes at right angles are of equal intensity. The faces on which the stresses act are supposed of unit width normal to the paper. Let $c\,a$ be the plane on which the stress p is wholly normal, making an angle θ with $c\,b$. Considering the equilibrium of $a\,b\,c$, resolving parallel to $a\,b$,

$$p \times a\,c \cos\theta = p_1 \times b\,c + q \times a\,b$$
$$= p_1\,a\,c \cos\theta + q\,a\,c \sin\theta,$$
$$p - p_1 = q \tan\theta \quad . \quad . \quad . \quad . \quad (27).$$

Resolving parallel to $b\,c$,

$$p \times a\,c \sin\theta = p_2 \times a\,b + q \times b\,c$$
$$= p_2 \times a\,c \sin\theta + q \times a\,c \cos\theta,$$
$$p - p_2 = q \cot\theta \quad . \quad . \quad . \quad . \quad . \quad (28).$$

Subtracting (27) from (28),

$$p_1 - p_2 = q\,(\cot\theta - \tan\theta) = \frac{2\,q}{\tan 2\theta},$$
$$\tan 2\theta = 2\,q/(p_1 - p_2) \quad . \quad . \quad . \quad . \quad (29).$$

An equation which gives two values of θ differing by a right angle, corresponding to the two principal planes. Multiplying (1) by (2),

$$(p - p_1)\,(p - p_2) = q^2,$$
$$p = \tfrac{1}{2}\,(p_1 + p_2) \pm \sqrt{\tfrac{1}{4}\,(p_1 - p_2)^2 + q^2} \quad . \quad (30),$$

which gives two values, p_x and p_y, which are the principal stresses.

The planes on which there are maximum shear stresses are inclined at 45° to the principal planes, and the greatest shear stresses on any planes in the solid are

$$q_{\max.} = \tfrac{1}{2}\,(p_x - p_y) = \sqrt{\tfrac{1}{4}\,(p_1 - p_2)^2 + q^2} \quad . \quad (31).$$

Given a normal stress on one plane and a shearing stress on this plane and another plane at right angles. This

particular case is of frequent occurrence. Putting $p_2 = 0$ in the equations just found,

from (28), $\tan\theta = q/p$ . . . . (32).

Substituting in (27),

$$p - p_1 = q^2/p,$$

$$p = \tfrac{1}{2}p_1 \pm \sqrt{\tfrac{1}{4}p_1^2 + q^2} \quad . \quad . \quad . \quad (33),$$

and the two values p_x and p_y of the principal stresses given by this equation substituted in equation (32) give the position of the principal planes. The planes of greatest shear stress are inclined at 45° to the principal planes, and the shear stress on these is given by the equation—

$$q_{\max.} = \tfrac{1}{2}(p_x + p_y) = \sqrt{\tfrac{1}{4}p_1^2 + q^2} \quad . \quad . \quad (34).$$

CHAPTER II

THE PLASTICITY AND HARDNESS OF MATERIALS

23. Plasticity in materials has long been recognised, and the terms malleable (capable of being hammered into sheets), ductile (capable of being drawn into wire), plastic (capable of being moulded), have been used with more or less clearness to denote the property of undergoing an indefinitely large deformation and retaining it permanently. The characteristic of plasticity is not the largeness of the deformation, but its permanence when the stress is removed. Cork may be compressed to one-eighth of its volume by a fluid stress, but it recovers its original volume again if the stress is removed, so much so that it has been proposed to use cork in gun compressors to absorb the force of recoil and restore it again. Cork is compressible in volume, not plastic. India-rubber can be extended to eight times its original length with little change of volume, but it recovers its figure when tension is relaxed. It has a long range of somewhat imperfect elasticity. But iron at welding heat takes any figure given to it in the rolls or under the hammer, and retains it. It is almost perfectly plastic.

In a paper by M. Henry Tresca, who first studied scientifically and carefully the plastic properties of solids, there is a passage which precisely indicates the relation of the phenomena of plasticity to those observed in ordinary testing:[1]

'For all bodies two distinct periods are recognised: the period of perfect elasticity, which corresponds to variations of length proportional to the forces applied; and the period of imperfect elasticity, during which, on the contrary, the changes of dimension increase more rapidly than the forces producing

[1] *Proc. Inst. of Mechanical Engineers*, 1878, 'The Flow of Solids,' by H. Tresca. See also a paper in the same *Proceedings* in 1876. Also *Cours de Mécanique Appliquée, professé à l'École Centrale*, by A. Tresca. Also numerous 'Memoires sur l'Ecoulement des Solides' in the *Comptes Rendus*.

them. If the second phase of deformation be alone considered, it is easily understood that it tends towards an ultimate condition in which a given force, sufficiently great, would continue to produce deformation, without limit—as may be observed in the process of drawing lead wire. This particular condition, in which the deformation is indefinitely augmented under the operation of a sufficiently great force, constitutes in fact the geometrical definition of a third period, the period of fluidity. The period of fluidity is more extended for plastic substances: it is more restricted, and will even disappear altogether, for some vitreous or brittle substances. But it is perfectly developed and extremely extended in the case of clays and of the most malleable metals.'

M. Tresca observed in early experiments with lead and similar plastic metals that the large plastic deformation was unaccompanied by any sensible change of density. Assuming a deformation without change of volume, M. Tresca has chiefly studied the geometrical conditions of the phenomena of plasticity. There is another feature of plastic deformation however, and that is the dependence of the deformation on time. Even within the elastic limit there is an internal molecular friction or viscosity resisting deformation of shape, and greater as the rate of deformation is greater. But the time influence is very much more marked in plastic deformation. Under a stress producing plasticity the deformation gradually increases either indefinitely or at a diminishing rate, as the time during which the stress acts is infinitely prolonged.[1]

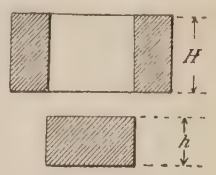


FIG. 20.

The following simple cases of nearly pure plastic deformation, selected chiefly from M. Tresca's Memoirs, will serve to indicate the geometrical laws of the deformation.

Suppose a cylindrical block of plastic substance supported on a die-block and perforated by a punch. It will be found that the height h of the punching or *wad* (fig. 20) is in general much less than that of the block H. Thus with a block 10 cm. high through which a hole 2 cm. diameter was punched, the wad was only 3 cm. high. A precise determination showed that there was no increase of density in the wad. Consequently during punching seven-tenths of the metal must

[1] See the article on 'Elasticity' in the *Encyclopædia Britannica*, by Lord Kelvin.

have flowed laterally into the block. A partially-punched nut (fig. 21) showed a wad having a thickness visibly less than the penetration of the punch. Some superposed discs of lead punched similarly and then divided showed the appearance sketched in fig. 22. The wad, like the original block, consisted of a series of discs, the lowest being nearly of the thickness

Fig. 21.

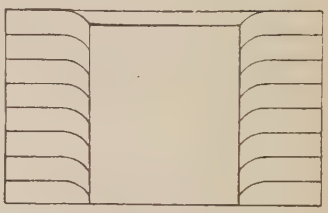


Fig. 22.

of the original discs, and the higher ones thinner. Of the metal forced laterally, therefore, the higher layers furnished the larger part. What happened in punching thick blocks is therefore now obvious. The metal under the punch becomes plastic and flows, till the remaining metal is so thinned that its resistance to shearing is less than the pressure on the punch.

24. *Formation of a Jet by Plastic Flow.*—Suppose a series of lead discs are placed in a strong cylinder (fig. 23) and subjected to pressure in an hydraulic press. If the pressure exceed a certain limit, and if there is an orifice in the bottom of the cylinder, the lead will flow like a liquid, forming a jet exhibiting contraction. Each disc originally superposed in the box contributes to form part of the jet. Let the thickness of the layers originally in the box be H, and let this be diminished after flow to h, while the jet attains a length l: let R be the radius of the box, and r that of the jet; then from the constancy of density of the lead we obtain the equation—

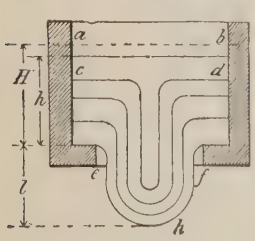


Fig. 23.

$$\pi \, \mathrm{R}^2 \, (\mathrm{H} - h) = \pi \, r^2 \, l,$$

$$\frac{l}{\mathrm{H} - h} = \frac{\mathrm{R}^2}{r^2} \quad . \quad . \quad . \quad . \quad (1).$$

Concentric Contraction of Central Cylinder.—Imagine in the block a cylinder of radius r (fig. 24) forming a prolongation of the jet, so that the lead in the chamber consists of an annulus of radii R and r, and a cylinder of radius r. When the thickness of the metal in the chamber diminishes by $a\,c = d\,h$, the material forced out of the annulus can escape neither towards the piston nor towards the sides of the chamber. It must necessarily flow into the space occupied by the central cylinder. From symmetry that cylinder will remain a cylinder, r diminishing to $r - d\,r$.

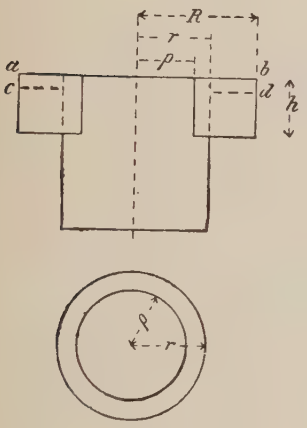


Fig. 24.

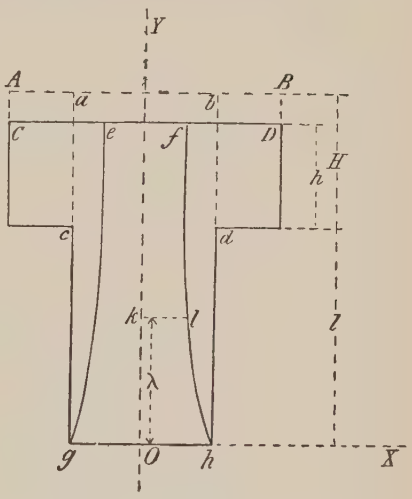


Fig. 25.

Equating the volume forced out of the annulus to the diminution of volume of the central cylinder—

$$\pi(\mathrm{R}^2 - r^2)\,d\,h = 2\pi\,h\,r\,d\,r,$$

$$\frac{dh}{h} = \frac{2r\,d\,r}{\mathrm{R}^2 - r^2} \quad . \quad . \quad . \quad . \quad (2).$$

Proportional Contraction of Cylinders forming the Central Cylinder.—Let fig. 24 represent in plan a section of the central cylinder. When that cylinder changes radius from r to $r - d\,r$, from matter forced in from the external annulus, any other cylindrical space of radius ρ must also diminish in radius. It is natural to suppose that the areas diminish proportionally, so that—

$$\frac{2\pi\,r\,d\,r}{\pi\,r^2} = \frac{2\pi\,\rho\,d\,\rho}{\pi\,\rho^2},$$

$$d\,r/r = d\,\rho/\rho \quad . \quad . \quad . \quad . \quad (3).$$

Transformation of Central Cylinder.—Let ρ be now the radius of the cylinder which was initially of radius r.

From (2)

$$\frac{dh}{h} = \frac{2r\,dr}{R^2 - r^2}.$$

Replacing dr from (3),

$$\frac{dh}{h} = \frac{2r^2}{R^2 - r^2}\frac{d\rho}{\rho}.$$

Integrating,

$$\log h = \frac{2r^2}{R^2 - r^2}\log \rho + c.$$

Let H, as in (1), be the initial height of the layers in the chamber. For $h = H$, $\rho = r$. Then—

$$\log H = \frac{2r^2}{R^2 - r^2}\log r + c.$$

Eliminating c,

$$\log \frac{h}{H} = \frac{2r^2}{R^2 - r^2}\log \frac{\rho}{r},$$

$$\frac{\rho}{r} = \left(\frac{h}{H}\right)^{\frac{R^2 - r^2}{2r^2}} \quad . \quad . \quad . \quad . \quad (4),$$

which gives the radius ρ of the portion of the central cylinder initially of radius r after any amount of flow into the jet.

If A B (fig. 25) is the original surface of the lead, C D the surface after the flow of the jet $c\,d\,g\,h$, then the matter initially occupying the central cylinder $a\,b\,c\,d$ will be found occupying the space $e\,f\,g\,h$, $e\,f$ being the diameter to which the original central cylinder is now reduced. Also $k\,l$ is the value of ρ when so much of the jet was formed that $k\,l$ was at $c\,d$, and $o\,k = \lambda$ was then the length of the jet.

Now in the equation (4) let ρ be the radius of the central cylinder when the length of the jet is l. But from (1)

$$h = H - \frac{r^2}{R^2}l,$$

$$\frac{\rho}{r} = \left(1 - \frac{r^2\,l}{R^2\,H}\right)^{\frac{R^2 - r^2}{2r^2}} \quad . \quad . \quad . \quad (5),$$

which is the equation to the curve $f\,h$, ρ being the abscissa when the ordinate measured above o x is l.

The curve varies with the value of $\frac{2r^2}{R^2 - r^2}$. If that quantity is greater than 2 the curve may be regarded as a parabola of a higher degree. If it is equal to 2 when $r^2 = R^2 - r^2$, or $r = R/\sqrt{2}$, the curve is a parabola of the second degree. If $r = R/\sqrt{3}$ the curve reduces to a straight line.

M. Tresca has experimentally verified the law; the verification proved entirely satisfactory.

25. *Pressure of Fluidity.*—These experiments show that a ductile body is deformed when the pressure exceeds a certain amount according to geometric laws, and permanently, so that there is no indication of elasticity or tendency to return to the primitive shape. M. Tresca designates by the term 'pressure of fluidity' the stress necessary to induce this state.

26. *Application to the Case of Prisms subjected to Tension or Compression.*—M. Tresca perceived that, in testing, a bar passed from the elastic state through an imperfectly plastic state to an almost perfectly plastic condition, but he has not investigated the phenomena which occur in testing. There is, however, a general relation deducible on the assumption of a condition of perfect plasticity which will be useful hereafter.

Suppose that in the deformation of a plastic bar the volume does not change, a condition nearly satisfied in the portion of a bar which draws down or locally contracts. Let l be the initial length and d the initial diameter of a bar which, when elongated plastically, has the length $l + \lambda$ and the diameter $d - \delta$. From the constancy of volume we get—[1]

$$\frac{\pi}{4} d^2 l = \frac{\pi}{4} (d - \delta)^2 (l + \lambda),$$

$$\left(\frac{d - \delta}{d}\right)^2 = \frac{l}{l + \lambda} \quad . \quad . \quad . \quad . \quad (6).$$

Now the contraction of area is—

$$\frac{\pi}{4} \left\{ d^2 - (d - \delta)^2 \right\} = \frac{\pi}{4} d^2 \frac{\lambda}{l + \lambda}.$$

Hence—

$$\frac{\text{contraction of area}}{\text{initial area}} = \frac{\lambda}{l + \lambda}. \quad . \quad . \quad . \quad (7).$$

[1] This deduction was given in the *Engineer*, May, 1885.

So that for a perfectly plastic material the percentage of contraction of area is not proportional to the percentage of elongation calculated on the original length of the bar, but to the percentage of elongation calculated on the stretched length of the bar.

During plastic elongation the intensity of the stress remains constant. Hence, the initial load on the bar when the plastic condition is reached is, if p is the pressure of fluidity—

$$P_1 = \tfrac{1}{4}\pi d^2 p.$$

Similarly, when the elongation is λ,

$$P = \tfrac{1}{4}\pi (d - \delta)^2 p.$$

Hence—

$$\frac{P}{P_1} = \left(\frac{d-\delta}{d}\right)^2 = \frac{l}{l+\lambda},$$

the load diminishing as the bar stretches. It will be seen that this phenomenon occurs in the last stage of a tensile test. If the stress is compressive,

$$\frac{\text{dilatation of area}}{\text{original area}} = \frac{(d+\delta)^2}{d_2} = \frac{l}{l-\lambda}\frac{P}{P_1}, \quad . \quad (8),$$

the load increasing as the prism shortens, as occurs in crushing short prisms.

27. *Work done in Plastic Deformation.*—Consider the case of a prism which shortens a length $d\lambda$, while the load increases from P to $P + dP$. The work done in compression is $P\,d\lambda$. But

$$P\,d\lambda = P_1 l \frac{d\lambda}{l-\lambda}.$$

Hence the work in compression from an original length l to a length $l - \lambda$ is—

$$W = \int^{\lambda} P_1 l \frac{d\lambda}{l-\lambda} = P_1 l \log_e \frac{l}{l-\lambda}.$$

But $P_1 = \frac{\pi}{4} d^2 p$, and putting v for the volume of the prism,

$$W = p v \log_e \frac{l}{l-\lambda}.$$

HARDNESS OF MATERIALS

Hardness is a property as to the definition of which physicists are not agreed, nor is any one method of measuring it generally adopted. Excluding quite brittle materials, which crush to powder under pressure, and with reference specially to the metals used in construction, hardness may be defined as resistance to permanent or plastic deformation. That definition accords with the ordinary meaning of the word hardness to engineers.

28. *Methods of determining Hardness.*—A mechanic tests hardness by using a file, and the earliest scientific scale of hardness is that proposed by Moh. He selected ten substances and arranged them so that each would be scratched by the substance next above it in order, and would scratch that next below. This simple scratch test has been very useful in the case of brittle bodies; but it is less useful for ductile bodies.

Seebeck and Franz (1850) used an instrument termed a sclerometer, having a steel or diamond point at the end of a balanced lever. The specimen was placed on a revolving table below the point, weights were added over the point till it just scratched the specimen. The weight required in grams was taken as the hardness number. The method requires some skill and is more suitable for brittle than for ductile materials. Professor T. Turner [1] used a modified form of sclerometer in which the balanced lever resting on a knife-edge was provided with a sliding weight. The lever was graduated so that each division on the scale corresponded to one gram at the scratching point. The lever also rested on a pivot so that the diamond point could be moved over a fixed specimen. The surface to be scratched was polished with emery and oiled. The following table gives some values of the hardness determined by this scratch method:

	Weight on diamond point in grams.
Lead	1
Commercial tin	2½
Annealed copper	8
Extra pure iron	17
Soft cast iron	18
Mild steel	21
Tyre steel	21–24
Hard scrap cast iron	40
Hard white cast iron	70

[1] *Proceedings of the Birmingham Philosophical Society*, 1886, vol. v. part ii.

INDENTATION TESTS

29. Various investigators have used an indentation test for determining hardness, and such a test is specially suitable for ductile materials. Calvert and Johnson[1] used as a measure of hardness of alloys the weight which caused a small truncated cone to indent the alloy to a depth of $3\frac{1}{2}$ mm. Major Wade used a hardened-steel pyramidal point, or knife-edge, as shown at A (fig. 26), held in a guide-block which could be placed in the testing machine. A pressure of 5 tons was used to force the point or edge into the specimen. Colonel Rosset improved this arrangement by adopting the form of point shown at B. The point consists of two knife-edges inclined at 163°, the angle of the knife-edges being 90°. Middleberg[2] used a curved knife-edge as an indenting tool in determining the hardness of tyres. The knife-edge was about $\frac{3}{4}$ inch long, ground to an angle of 30°, and having an edge curved to 1 inch radius. The knife-edge placed on the tyre was loaded with 6,000 lbs., and the reciprocal of the length of indentation was taken as the measure of hardness. Martel[3] has described an indentation test in use at the foundry of Ruelle. The indenting tool is a pyramidal point very accurately ground to an exact pattern. Indentation is produced by a falling weight. The volume of indentation is calculated from one measurement of the length of the indentation. It appears that the volume of indentation for any one metal is nearly proportional to the work of the falling weight.

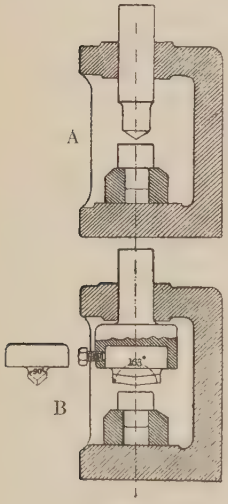


Fig. 26.

Let l be the measured length of an indentation produced by a given weight falling a distance h. The proportionality of work and volume of indentation leads to the equation $l = \text{K}\sqrt[3]{h}$, where K is a constant. For the weight P, falling a given height, $l = \text{M}\sqrt[3]{\text{P}}$, where M is a constant. Both these equations

[1] *Philosophical Magazine*, 4th series, vol. xvii. p. 114.
[2] *Engineering*, 1856, vol. ii. p. 481.
[3] *Commission des Méthodes d'Essai des Matériaux de Construction*, tome ii. p. 261.

were verified experimentally with different weights, P, falling different heights, h. It appears also that, for the same weight and height of fall, the volume of indentation in any metal was nearly the same with indenting tools of somewhat different form. Hence, generally, if V is the volume of indentation produced by a weight P, falling a distance h, $V = P h / D$, where D is the work required to produce unit volume of indentation by the given tool in the given metal. D is taken as the measure of the hardness of metal. Martel's method is simple; it gives definite results, and the only objections to it seem to be that it is not always convenient to use a heavy falling weight to produce the indentation.

HARDNESS

	Values of D
Tool steel, tempered at cherry red in oil	420
„ „ not tempered	415
Steel gun tubes tempered in oil	455–300
Cast iron for guns	300–208
Rolled wrought iron	226
Bronze	154
Copper	156
Cast lead	9

Recently A. Föppl[1] has described another method. Two cylindrical test specimens are prepared and polished, the radius being 20 mm. (0·8 inch); these are laid one on the other crossways and pressed together in a testing machine. It is found that the surface of indentation is proportional to the pressure applied, and that therefore the pressure per unit area of surface flattened by indentation is a measure of hardness. The numerical value of the hardness, h, depends on the radius of the cylindrical surfaces, the product $h^3\sqrt{r}$ being constant. It is not clear that any advantage is gained by using a material to indent itself instead of using a steel indenting tool. Probably the false idea that the sharpness of the indenting tool considerably affected the result was of influence in determining the form of Föppl's test.

30. *The Author's Method of Measuring Hardness.*[2]—The indenting tool is a straight knife-edge; the test specimen indented is a short bar of square section; and indentation is produced by a steady load. A series of observations of indentation and load are taken, from which a constant is

[1] *Ann. Phys. Chem.* 63, i. pp. 103–8.

[2] 'A New Indentation Test for Determining the Hardness of Metals.' *Proc. Inst. of Civil Engineers*, vol. cxxix. 1897.

deduced, which is the measure of hardness. The indenting tool is a simple short bar of square tool steel, *a* (fig. 27), ground accurately, so that the angles are right angles and as hard as possible. Any one of the edges can be used as an indenting edge, and the tool is easily reground. The test piece, *b*, is a square bar of the metal to be tested, about $2\frac{1}{2}$ inches long, and, in the author's tests, usually $\frac{1}{2}$ inch square. The tool *a* (fig. 27) is carried in an apparatus which ensures parallel movement, and which has a scale and vernier *f* for measuring the indentation. The apparatus is placed in an ordinary testing-machine, loads are applied, and the indentation corresponding to each is noted. Each load rests on the specimen *e* a few minutes, till the indentation ceases to increase. If the load is increased sufficiently, the test specimen

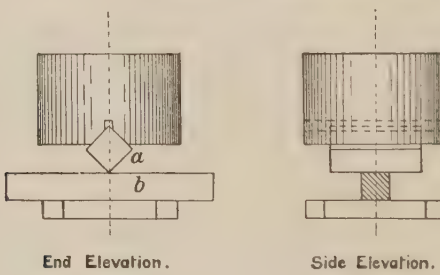


FIG. 27.—INDENTING TOOL

shears through or tears at the section *a b* (fig. 28), below the knife-edge. The test must not be carried so far. With metals which have a low yield point, such as some of the brass alloys, the load may produce a stress on *a b* which causes very sensible stretching. If that occurs, the indentations increase more rapidly. The point at which this stretching begins is well marked, if the indentations are plotted. The loads at which the indentations are measured should be less than the load at which this yielding of the specimen below the knife-edge begins. The depth of indentation, *i*, for each load is the quantity noted in the tests. With $\frac{1}{2}$-inch bars it was found that there was no stretching below the knife-edge with loads less than 6 tons per inch width for brass, nor with loads below 9 tons per inch width for steel.

Description of the Apparatus.—Fig. 29 shows the apparatus used in the tests. A cast-iron guide-block, *a*, has a loosely-fitted plunger, *b*, to which pressure is applied in

the testing-machine through a block, *c*, which forms, with the plunger, a spherical joint; *d* is the indenting tool, and *e* the test-piece resting on a plate of hardened steel, which in an improved apparatus had a spherical under-surface resting in a cup; *f* is a guide carrying a scale and vernier by which indentations can be read to $\frac{1}{1000}$ of an inch. There is a slight compression of the apparatus which is read as part of the indentation, but the correction for this is easily ascertained.

31. *Relation of Load and Indentation.*—To find a relation

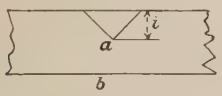


FIG. 28.

between the load and indentation, the results of a series of tests on bars of different metals were plotted in this way. The logarithms of the loads per inch width of bar were plotted as ordinates and the logarithms of indentations as abscissæ (fig. 30). For each bar the plotted points lie very nearly along a straight line, and for very different metals the slope of the lines is nearly the same.

Hence the relation,

$$c\,i = p^n \quad . \quad . \quad . \quad (9),$$

may be assumed, where p is the pressure per inch width of knife-edge in tons and i the

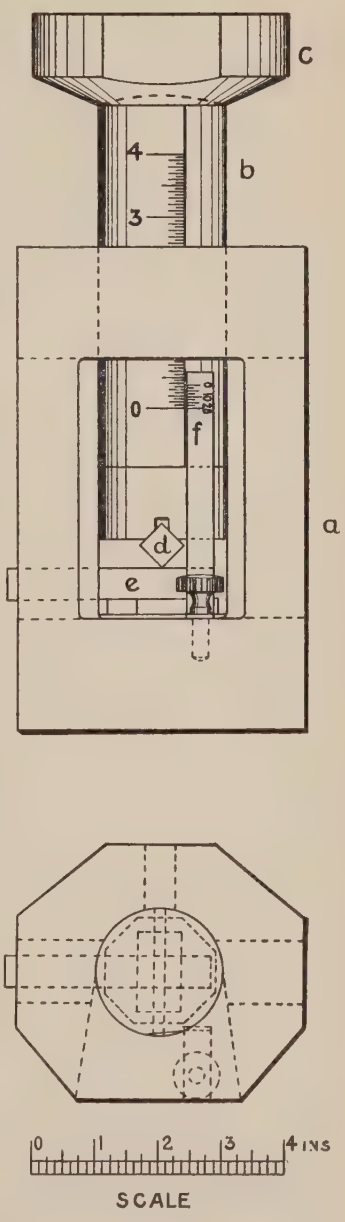


FIG. 29.

indentation in inches; n is the slope of the line obtained by plotting the logarithms of p and i, and c is a constant for the metal tested.

The following are the values of n obtained by measuring the plotted lines:

Material	Values of n
Cast tool steel, normal	1·17
Brass, No. 2	1·15
Brass, No. 1	1·16
Mild steel, normal	1·20
Copper, unannealed	1·20
„ annealed	1·18
Aluminium alloy	1·23
„ pure	1·19
Zinc	1·14
Lead, cast	1·23

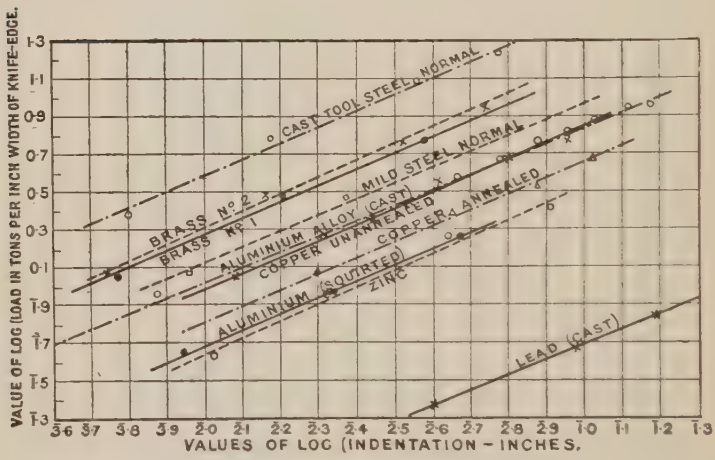


Fig. 30.

It will be seen that these values vary little, and no one differs much from 1·20. Hence the equation $c\,i = p^{1\cdot2}$ may be taken as the approximate relation between load and indentation, provided the loads do not exceed that at which sensible stretching below the knife-edge begins. Also, as c is the only constant which varies with the hardness of different materials, being larger with hard materials and smaller with softer materials, c may be taken as the measure of hardness. Obviously c can be determined by a single observation of load and indentation. But it is better to measure the

indentation corresponding to three or four loads, and thence to deduce a mean value of c.

32. *Tests of Square Bars of Different Metals.*—The test-bars were in most cases $\frac{1}{2}$ inch square and $2\frac{1}{2}$ to 3 inches long. Generally three indentations were made in each bar, and the mean of the three series of readings was taken in reducing the results.

Using the formula already given, and putting p for the load on the knife-edge in tons per inch width, and i for the depth of indentation in inches, and taking $n = 1{\cdot}2$, the following are the values of c obtained.

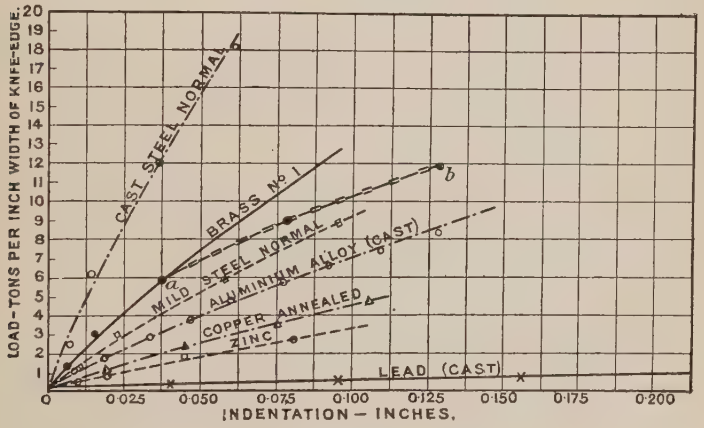


Fig. 31.

Hardness

	Values of c
Cast steel, normal	554·0
Mild steel, „	143·5
Copper, annealed	62·0
„ unannealed	105·2
Brass, No. 1	221·0
„ No. 2	246·0
Aluminium, squirted	41·8
„ alloy, cast	103·5
Lead, cast	4·2
Zinc, cast	40·8

If these numbers are compared with those given by Martel, it will be seen that for the same metals they are not widely dissimilar. Apparently the differences of hardness by the author's methods are somewhat greater. Fig. 31 shows the principal tests plotted in curves. The curves are drawn

with the calculated values, and the observed values are shown by dots. In the case of Brass, No. 1, the dotted line *a b* corresponds to loads beyond the limit at which sensible stretching of the specimen below the knife-edge begins. It will be seen how marked the increase of indentation is in that case. The constant c is of course obtained for loads less than that corresponding to the point *a*.

33. *Influence of Width of Test Bar on the Load per Inch Width to produce a given Indentation.*—The test-pieces used were all square bars, and it was found that for equal loads per inch width the indentations were nearly the same in bars of different width; they are, however, not exactly so.

Tests made on copper bars 0·75, 0·50, 0·25 inch in width showed that for a very ductile material the values of c varied nearly as the cube root of the width of bar. Hence for comparable results a standard size of test bar should be adopted. The author now uses test bars ½ inch square and 2½ inches long.

34. *Tests of Steel in Different Conditions.*—By far the most useful application of a hardness test would be the discrimination of the qualities of steel due to differences of treatment as to annealing and tempering.

Fig. 32 shows the results on two qualities of steel. The word *normal* is used for the steel as received.

The following are the values of c from these tests:

HARDNESS

	Values of C
Mild steel, normal	143·5
„ annealed	141·9
„ hardened	186·7
Cast steel, normal	554·0
„ annealed, A	538·0
„ „ B	503·0
„ „ C	527·0
„ hardened in oil	866·0

The mild steel hardens very slightly, nor is it much softened by annealing, being clearly as received in a well-annealed condition. On the other hand, the cast steel softens more when annealed, and increases much more considerably in hardness when tempered in oil. The numbers appear to discriminate the qualities sufficiently well.

35. *Influence of Sharpness of Knife-edge.*—The knife-edges used are very easily made and ground true. For hardening

them a material termed 'durol' has been used, and it seems to give a harder edge than simple water hardening. To find whether the sharpness of edge in any way affected the results, a tool with one edge quite sharp and the three other edges blunted more or less was tried. The width of edge of the blunted edges was apparently about 0·002, 0·008, and 0·012 inch. The following are two sets of observations of the indentation per ton per inch width of knife-edge for the copper and per $2\frac{1}{2}$ tons per inch for steel :

—	Sharp	Slightly blunt	Blunt	Very blunt
Copper . . .	·0155	·016	·016	·017
Mild steel . .	·026	·026	·027	·027

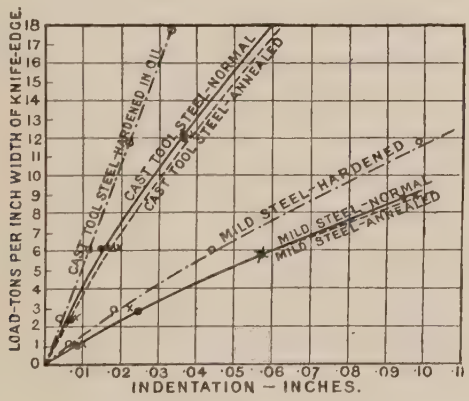


Fig. 32.

The differences are small, and it does not appear that the precise degree of sharpness of the knife-edge affects the results sensibly.

36. *Hardness Tests of Steel Rails.*—These tests were made with test bars $\frac{1}{2}'' \times \frac{1}{2}'' \times 2\frac{1}{2}''$. With such steel as is used for rails, and with loads on the knife-edge not exceeding 10 tons per inch width, it was found that the more simple approximate equation,

$$p = c_1 i \quad . \quad . \quad . \quad (9a),$$

represented the results accurately enough, c_1 being nearly constant for any given specimen. The value of the hardness number c_1 varied from 195 to 256 in different steel rails.

There was a striking agreement in the order of the hardness numbers and the percentage of carbon in the rail determined by chemical analysis. Where there was a discrepancy some other hardening element was present in exceptional proportion.

Steel Rails

Hardness number c_1	Carbon per cent.	Manganese per cent.	Phosphorus per cent.
195	0·33	0·69	0·06
205	0·37	0·80	0·06
221	0·33	0·84	0·10
237	0·38	0·56	0·10
245	0·41	0·91	0·07
256	0·41	1·14	0·08

The following table gives a comparison of the tensile strength, τ, and hardness number, Ξ, for a series of rails.

Test of Rails

Carbon per cent.	Tensile strength tons per sq. in. τ	Elongation in 8 ins. per cent.	Hardness number (Unwin) Ξ	Ratio $\frac{\tau}{\Xi}$
0·329	36·4	19·0	195	0·187
0·338	36·9	18·7	211	0·175
0·398	37·2	17·1	235	0·158
0·374	37·6	19·3	195	0·193
0·291	38·9	15·0	215	0·181
0·335	39·4	16·8	221	0·178
0·371	39·5	17·4	205	0·193
0·386 [1]	40·1	15·1	237	0·170
0·434	41·4	16·8	236	0·176
0·348	42·7	16·4	238	0·183
0·412	43·8	16·1	245	0·179
0·371	45·3	14·1	254	0·178
0·415 [2]	50·5	12·6	256	0·197
			Mean .	0·181

[1] Highest silicon. [2] Highest manganese.

Fig. 33 shows the plotting of the loads and indentations for some of these rail tests. It will be seen how nearly linear is the relation of p and i up to some limit of loading.

37. *Comparison of the Indentation and Scratch Methods of determining Hardness.*—Mr. Bertram Blount was good enough to determine by the scratch method the hardness of some of

the specimens previously submitted to an indentation test. In the scratch test a diamond point, balanced at the end of a lever, is dragged over a polished part of the specimen. The diamond point is loaded till it just definitely scratches (not merely marks) the surface. The load necessary is taken as the hardness number. The following table contains the hardness numbers by the scratch and indentation methods and their relative values, copper being taken as unity. It will be seen that the relative hardness follows the same order in both methods.

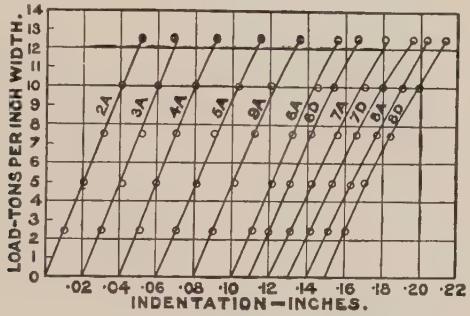


Fig. 33.

Hardness of Metals by Indentation and Scratch Methods

	Hardness number		Relative Hardness Copper = 1	
	Indentation method	Scratch method	Indentation method	Scratch method
Cast steel (normal)	554·0	25·0	8·94	4·17
Brass, No. 1 . . .	221·0	12·0	3·57	2·00
Mild steel (normal)	143·5	9·0	2·32	1·50
Copper (annealed)	62·0	6·0	1·00	1·00
Aluminium (squirted)	41·0	4·0	0·67	0·66

38. *The Brinell Hardness Test.*—Mr. J. A. Brinell introduced a method of determining hardness which has been extensively adopted on the Continent. He uses a hardened steel ball which is forced into the material tested, generally at a polished face, by statical pressure. Let P be the pressure in kgms., D the diameter of the ball, d that of the

impression, and h the depth of the impression, all in millimetres. Then, on the supposition that the ball is not deformed,

$$h = \tfrac{1}{2}\,(D - \sqrt{D^2 - d^2})\ \text{mm.},$$

and the area of the surface of the indentation is—

$$A = \pi\, D\, h = 1{\cdot}571\ D\ (D - \sqrt{D^2 - d^2})\ \text{sq. mm.}$$

Then the Brinell hardness number is—

$$H = P/A = P/(\pi\, D\, h)\ \text{kgms., per sq. mm.} \quad . \quad (10).$$

If H is calculated in lbs. per sq. in. it is converted into the Brinell number by multiplying by 0·000703.

With iron and steel Brinell used balls of 10 mm. diameter and a pressure of 3,000 kgms. For softer materials he suggested a pressure of 500 kgms. The diameter of the impression is measured with a wedge scale or vernier microscope to an accuracy of about $\frac{1}{20}$th of a mm. Brinell observed that with higher pressures or smaller balls the value of H for a given material was higher. Tests by Brinell and Benedick showed that for iron and steel within the range of the tests the quantity $(P/A)\sqrt[5]{D}$ was nearly constant. Hence, if H_1 is the value of P/A with a ball of diameter D_1, Brinell's hardness number is—

$$H = H_1 \sqrt[5]{(D_1/10)}. \quad . \quad . \quad . \quad (11).$$

For electro steel with 1·4 per cent. carbon, $P = 500$;

$\frac{1}{2}$ D mm. . .	1·6	2·49	2·99	3·97	5·00	6·37
H_1	306	288	277	263	253	239
$H_1\sqrt[5]{(D/2)}$.	366	346	344	346	350	346

To take into account varying statical pressures, Lechatellier proposed the following formula. Let H be the hardness number for a 10 mm. ball and a pressure of 3,000 kgms.; H_{DP} the hardness number P/A obtained with a ball of diameter D and a pressure P, then for steel Brinell's hardness number is—

$$H = H_{DP} \sqrt[5]{\frac{D}{10} \cdot \frac{20000}{17000 + P}} \quad . \quad . \quad (12).$$

But the equation is not very trustworthy.

Moore found that the depth of indentation in a Brinell test should not exceed one-seventh of the thickness of the test specimen, and the centre of the indentation should be at least $2\frac{1}{2}$ times its diameter from the edge of the specimen.

Martens has proposed to determine the hardness from the pressure and depth of indentation. He has constructed a ball apparatus which allows the measurement of the depth of indentation to 0·01 mm. He shows that with balls of 5 mm. diameter the ratio P/h is constant within a depth range of 0·05 mm. He takes the hardness number to be the load necessary to indent the material to a depth of 0·05 mm.

39. *Ludwig Cone Hardness Tests.*—The use of a hardened cone (fig. 34) instead of a ball is intended to simplify the Brinell test. Hardness numbers independent of the load can only be expected if the impressions with different loads are geometrically similar. The cone pressure hardness is defined to be the pressure producing the indentation in kgms. per sq. mm. of permanent impression. The cone angle is 90°. Let d be the diameter and h the depth of the indentation. Then the area is—

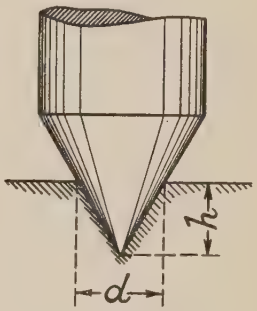


Fig. 34.

$$A = \tfrac{1}{4}\,\pi/d^2\sqrt{2} = 1{\cdot}11\ d^2 = 4{\cdot}44\ h^2 \text{ sq. mm.}$$

The hardness number is P/A kgms. per sq. mm. The measurement of h is more expeditious than that of d, and the cone pressure test is very similar to the test proposed by the author. Messrs. Amsler Laffon & Sohn of Schaffhausen construct a special instrument for these cone tests. The ratio of tensile strength to cone hardness number is on the average 0·335. The carbon percentage did not appear to exercise much influence on this ratio. In the cone test and the author's wedge indentation test, an error in the ball test due to the deformation of the ball by the pressure seems to be obviated.

40. *Impact Ball Hardness Tests.*—An indentation produced by impact has sometimes been used in determining hardness. Brinell has compared the pressure necessary in a statical test

and the energy in an impact test to produce the same indentation. He found that with iron containing 0·1 per cent. of carbon and a 10 mm. ball, an impact energy of 2·25 kilogram-metres produced the same indentation as a static pressure of 3,000 kgms. But the relation was different with harder steels.

41. *Variation of Hardness in Steels made by Different Processes.*.—A very valuable research has been made by Mr. F. W. Harbord on the properties of steels made by acid and basic, Bessemer and open hearth processes.[1] Only a selection of the results can be given here. The steels were tested both as rolled and heated to 620° C.

Composition		Tensile strength tons per sq. in.		Brinell's hardness number	
C per cent.	M per cent.	As rolled	Annealed	As rolled	Annealed
		Acid Bessemer			
0·10	0·51	26·8	26·0	100	96
0·24	0·90	34·6	34·2	111	111
0·44	0·88	41·5	40·9	139	135
0·55	0·86	51·9	44·6	151	147
0·74	1·07	62·9	57·1	167	161
		Basic Bessemer			
0·07	0·35	23·5	23·4	76	81
0·12	0·67	28·8	28·8	96	96
0·36	0·83	38·7	36·3	114	119
0·50	0·90	48·0	46·4	143	141
		Acid Open Hearth			
0·13	0·40	25·5	25·4	82	78
0·31	0·58	33·4	33·1	106	102
0·50	0·67	45·8	44·1	142	137
0·67	0·60	55·7	52·2	172	161
		Basic Open Hearth			
0·12	0·40	24·5	24·2	78	78
0·35	0·85	37·8	36·3	122	116
0·45	0·72	42·5	40·1	120	118
0·60	0·71	51·5	49·2	141	136

Broadly, the results show that a basic open hearth steel containing 0·5 per cent. carbon has the same hardness as an acid Bessemer steel containing 0·40 per cent. carbon.

42. *Relation between the Brinell Hardness Number and the Tenacity.*—In the case of steel the hardness number and the

[1] *Iron and Steel Institute*, 1907.

tenacity increase together and there is an approximately fixed ratio between them. For Fagersta steel Brinell found that the tensile strength in kgms. per sq. mm. was given very approximately by multiplying the hardness number by 0·346. Dillner made tests with seven series of steels containing 0·1 to 1·2 per cent. of carbon annealed at 860° C. These tests show that the ratio (tensile strength)/(hardness number) decreases with the percentage of carbon. The following table gives the mean results of Dillner's tests and also those of some tests by Charpy :

Brinell's hardness number	Ratio	
	Ball pressure normal to fibres	Ball pressure parallel to fibres
	Dillner	
Below 175	0·362	0·354
Above 175	0·344	0·324
	Charpy	
Below 175	—	0·351
Above 175	—	0·336

Charpy's hardness numbers were obtained with an 8 mm. ball and 4,000 kgms. pressure. Ratios obtained by the author have already been given (§ 36) in English units.

CHAPTER III

STRESS-STRAIN DIAGRAMS

43. Suppose a prismatic bar of uniform cross-section placed in a testing-machine, and an axial load on the bar gradually increased, while measurements are made of the length of a marked portion of the bar termed the gauge length. For every value of the load there will be a corresponding value of the stretch (or compression). The deformations may be plotted as abscissæ and the loads as ordinates, and points will be obtained on a curve giving the relation of load and strain for the whole test. This may be termed a *load-strain* diagram. If the scales of abscissæ and ordinates are altered so that the former represent extensions per unit length and the latter stresses per unit of original cross-section, the diagram may be termed a *stress-strain* diagram.

For a perfectly elastic bar the loads or stresses are proportional to the strains. Hence the curve is a straight line, such as A O B (fig. 35). By setting off compressions to the left, extensions to the right, thrusts downward, and tensions upward, a continuous line is obtained representing the relation of stress and strain for the whole range of perfect elasticity of the bar.

For a perfectly plastic bar the load would have to attain some value, P = O C or — P = O E, these being so-called 'pressures of fluidity,' before plastic deformation commenced. In a bar in compression the section increases as it shortens. Hence, since the pressure per unit of area in a plastic material is constant, the load must increase. In a bar in tension the section contracts as the bar elongates, and hence the load must be diminished as the elongation increases, if it is to be kept in equilibrium with the resistance of the bar. Hence curves giving the relation of stress and strain during plastic deformation are curves such as C D or E F.

It has been shown (§ 26) that the relation of stress and strain during plastic deformation is—

$$P_1 = P \frac{l}{l \pm \lambda},$$

where P_1 is the load which causes a deformation $\pm \lambda$ in a length l. This shows that the curves C D, E F are parts of hyperbolas having O X and G O′ H as asymptotes, where G O′ H is at a distance l from C O E.[1]

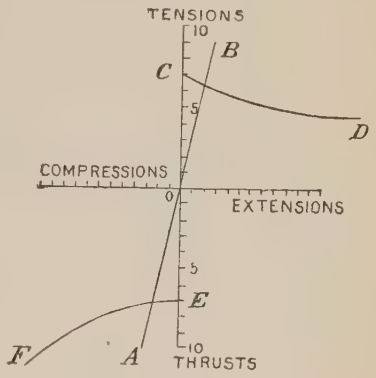


FIG. 35.

Before examining some stress-strain diagrams for different materials it may be pointed out that quite similar diagrams are obtained by plotting moments of torsion and angles of twist, or bending moments and deflections.

44. *Stress-strain Curves for a Brittle Material.*—A brittle material may be defined as a material which breaks without any considerable plastic deformation. Various cast metals may be taken as examples of materials approaching to this description.

The right-hand curve in fig. 37 shows the stress-strain diagram from Hodgkinson's experiments on long cast-iron bars. No part of the curve, except perhaps

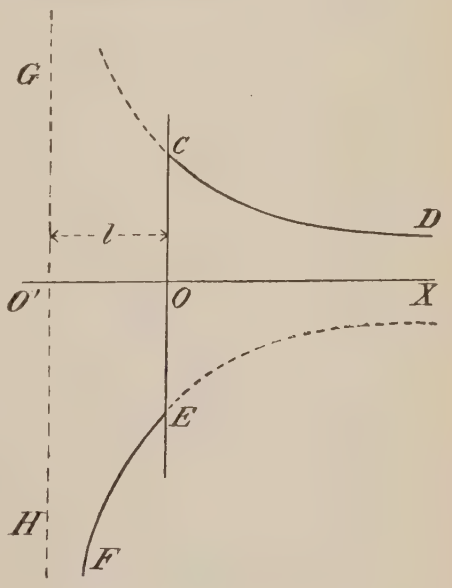


FIG. 36.

[1] An account of stress and strain diagrams, indicating the different character of the elastic and plastic portions of the curve, was given by the author in the *Engineer* for May 22, 1885, and also in a lecture at the Society of Arts on Autographic Diagrams, February 1886.

a short portion near the origin, is quite straight. Materials

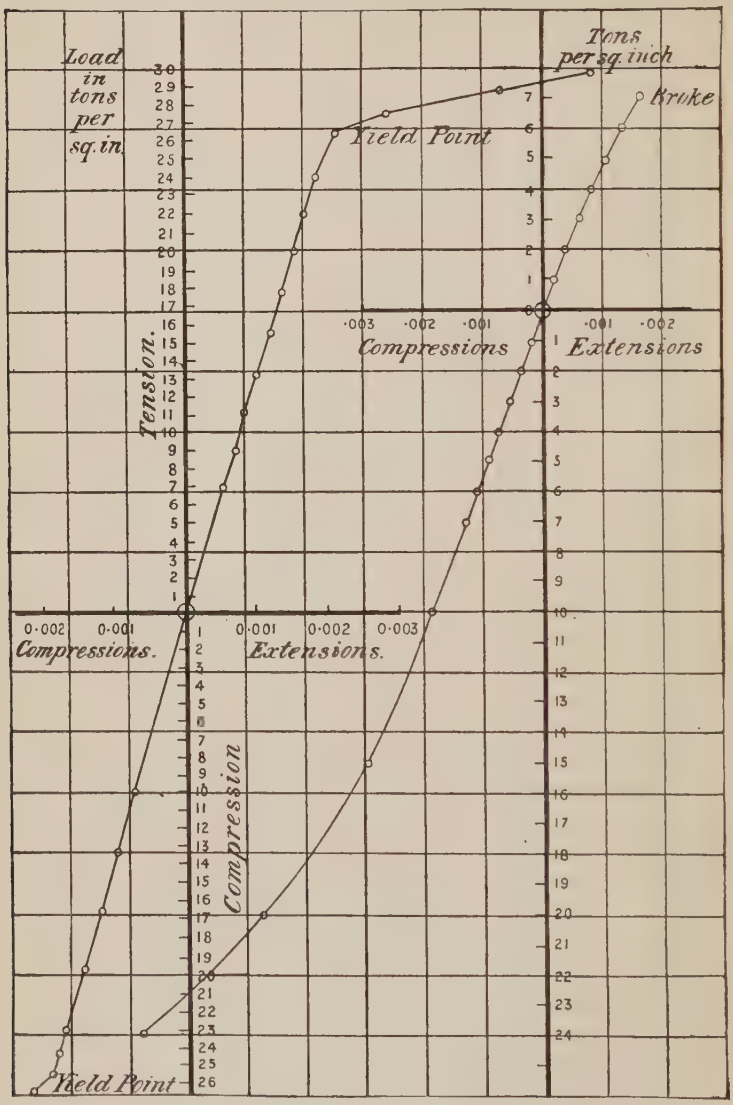


Fig. 37.—Stress-strain Curves for Cast Iron and Mild Steel.

like cast iron take a sensible though small set even with comparatively small loads, and the set increases regularly with

the loads. Such materials have, strictly speaking, no elastic limit when first subjected to stress. Further, in materials like cast iron or steel castings, the bar breaks before any great plasticity is exhibited. The curve runs to the breaking-points in tension and pressure without any great or significant change of curvature.

Hodgkinsons's results for cast iron are very approximately expressed by the equations,[1]—

$$\text{Tension} \quad p = 6{,}220\,e - 1{,}298{,}000\,e^2$$
$$\text{Thrust} \quad p = 5{,}773\,c - 233{,}500\,c^2$$

where p_t and p_c are the tensile and compressive stresses in tons per sq. in. and e and c the corresponding extensions and compressions per in. length.

The following short table gives a comparison of the extensions and compressions for different loads:

Cast Iron

Load in tons per sq. in.	Extension per unit length	Compression per unit length	Increase of extension per ton per unit length	Increase of compression per ton per unit length
1	·000166	·000174	·000166	·000174
2	·000347	·000351	·000181	·000177
3	·000544	·000531	·000197	·000180
4	·000765	·000714	·000221	·000183
5	·001021	·000899	·000256	·000185
6	·001338	·001090	·000317	·000191
7	—	·00128	—	·000190
9	—	·00167	—	·000195
12	—	·00229	—	·000207

45. *Elastic Stress-strain Curve.*—Many rolled materials are almost perfectly elastic, both for tension and compression, for a considerable range of stress. The left-hand curve in fig. 37 gives the stress-strain curves, up to the points just beyond the elastic limits in tension and compression, for two bars of mild steel, tested by the Committee of Civil Engineers.[2] The steel was cast steel suitable for piston rods. The bars were $1\frac{1}{2}$ inch diameter, and the deformation was measured by verniers in a length of 10 feet. The numbers given in the following table are taken from a plotting of the results

[1] Unwin, *The Engineer*, October 29, 1886.

[2] *Experiments on the Mechanical and other Properties of Steel.* By a Committee of Civil Engineers, 1870.

to a large scale. The steel broke at 41·85 tons per sq. in. in tension.

STEEL

Stress in tons per sq. in.	Extension per unit length	Compression per unit length	Extension per ton per sq. in. per unit length	Compression per ton per sq. in. per unit length
7	·00054	·00050	·000077	·000071
10	·00076	·00072	·000076	·000072
15	·00112	·00108	·000075	·000072
20	·00150	·00146	·000075	·000073
25	·00192	·00188	·000077	·000075
30	·00583	—	--	—
Means			·000076	·000073

It will be noticed that the deformation per ton per sq. in.

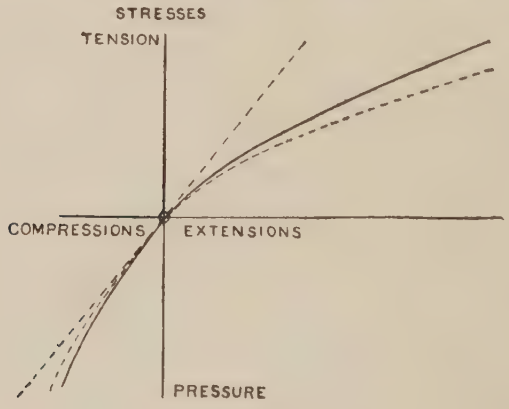


FIG. 38.—THE STRONG LINE SHOWS THE IMMEDIATE STRAIN, THE DOTTED THAT AFTER SOME MINUTES.

is nearly constant, and nearly the same for tension and compression. Hence the results plot nearly into a continuous straight line. Beyond 26 tons per sq. in. the elastic limit in tension and compression is passed, and the deformations quite abruptly become larger.

46. *Stress-strain Diagram for India-rubber.*—India-rubber supplies an example of a solid in which the deformations are not small compared with the original length. It has besides great incompressibility of volume, so that under considerable alterations of form its volume is nearly constant. India-rubber

is not easily held in grips in tension tests, but it is quite satisfactory to use a ring of india-rubber stretched between pins. The gauge length does not affect the percentage of elongation. Dr. Winkler has given the following results of experiments on india-rubber in tension and compression:

p = load in kilograms per sq. cm. of initial area.

λ = elongation or compression of unit length.

λ' = elongation or compression when the load has been some time on the bar.

The — signs refer to compression; the + signs to tension:

Compression			Tension		
p	λ	λ'	p	λ	λ'
− 0·5	− ·036	− ·036	+ 0·5	+ ·046	+ ·052
1·0	·076	·082	1·0	·121	·137
1·5	·109	·115	1·5	·207	·264
2·0	·139	·147	2·0	·316	·396
2·5	·163	·173	3·0	·548	·698
3·0	·185	·198	4·0	·859	1·135
—	—	—	5·0	1·309	1·572
—	—	—	6·0	1·794	2·110

Fig. 38 shows these results plotted. It will be seen that the stress-strain curve is without any straight portion, the elongations increasing faster and the compressions less fast than the stresses. The modulus of elasticity, $E = p/\lambda$, calculated in the ordinary way, is therefore extremely variable. The section contracts so that the volume of the bar remains constant. Then the real stress in the bar is $p_1 = p\ (1 + \lambda)$. Then the modulus of elasticity, calculated from the real stress and the elongation per unit of initial length, is—

$$E_1 = \frac{p_1}{\lambda} = p\,\frac{1+\lambda}{\lambda} = E + p;$$

and the modulus, calculated from the real stress and the elongation λ_1 per unit of stretched length, is—

$$E_2 = \frac{p_1}{\lambda_1} = \frac{p\ (1+\lambda)^2}{\lambda}$$

$$= E_1\ (1+\lambda); \quad = E_1 + p_1; \quad = E + p\ (2+\lambda).$$

The following table gives values of E, E_1, and E_2. It will be seen that for a considerable range of stress E_2 is even more constant than E_1, and both are more constant than E:

Load p	Real stress p_1	E	$E_1 = E + p$	$E_2 = E_1 + p_1$	
− 3·0	2·45	16·2	13·2	15·6	
− 2·5	2·09	15·3	12·8	14·9	
− 2·0	1·72	14·4	12·4	14·1	
− 1·5	1·34	13·8	12·3	13·6	Mean 13·7
− 1·0	·92	13·2	12·2	13·1	
− 0·5	·48	13·9	13·4	13·9	
0	0	—	—	—	
+ 0·5	·52	10·9	11·4	11·9	
+ 1·0	1·12	8·3	9·3	10·4	Mean 11·4
+ 1·5	1·81	7·2	8·7	10·5	
+ 2·0	2·63	6·3	8·3	10·9	
+ 3·0	4·64	5·5	8·5	13·1	
+ 4·0	7·44	4·7	8·7	16·1	
+ 5·0	11·55	3·8	8·8	20·3	
+ 6·0	16·76	3·4	9·4	26·2	

47. *Load-strain Curve for Ductile Materials.*—In soft wrought iron and steel the load-strain curve has the form shown in fig. 39. Between the elastic limits A and C the curve is very nearly a straight line. The parts A B and C D correspond to a partly plastic condition of the material in which the larger part of the deformation is permanent. In tension a maximum load is reached at D, but the deformation can be continued with a diminishing load till the bar breaks at some point E. During the part D E the curve falls very rapidly, because a local drawing out begins, and the cross-section diminishes considerably over a small portion of the bar. In the compression curve A B there is a more gradual change of curvature, because the section increases instead of diminishing. Up to the points A and C there is almost immediate equilibrium between the stress and strain. But in the parts A B and C D the deformation is to some extent gradual, and requires time for its completion. Beyond the elastic limits at A and C the partly plastic extension proceeds regularly again. But the precise extension for any load between C and D depends more or less on the time during which the load acts. During any pause in this part of the curve the extension increases without increase of load, to an extent which differs with different materials; and when the load is increased again the rigidity of the bar is found to be greater than before, and the curve becomes steeper (figs. 45, 51). Next to the yield point, the most important point to observe is the point D, where the maximum load is reached. For this point it would be

convenient to have a name, and the term *plastic limit* may be suggested. Beyond D a part of the bar behaves almost like a perfectly plastic body. It is at the point D that the phenomenon of local drawing out of the bar begins which is characteristic of the last stage of the test. At some load less than the maximum load, indicated on the diagram at E, the bar breaks at the local contraction.

It is convenient to follow the German practice, and to call the critical points the P, the S, the B, and the Z limits, and to denote the corresponding stresses by p_P, p_S, p_B, and p_Z; also the elongations per unit of gauged length by λ_P, λ_S, λ_B, λ_Z.

48. *Load-strain Diagram in a Tension Test of Ductile Material.*—In the case of some hammered or rolled materials like wrought iron or mild steel, the stress-strain line in tension (fig. 40) is very approximately a straight line up to some point P, so that stresses and strains are proportional, and the extensions are elastic and completely vanish if the stress is removed. Bauschinger terms the point P the *limit of proportionality* or real elastic limit. Beyond P there is a sensible deviation from proportionality, the strains increasing faster than the stresses, also the strains are partly permanent or *sets*. In many very ductile materials there is beyond P an extremely well-marked point S, where the extensions increase very rapidly and without increase of load. This is termed the *yield point* (in German *Streckgrenze*). The point was first noticed in the diagrams of the Committee of Civil Engineers appointed to make experiments on steel ('Experiments on Steel,' 1870). This point is much more easily determined than the limit of proportionality, and in commercial testing is often termed inaccurately the elastic limit.

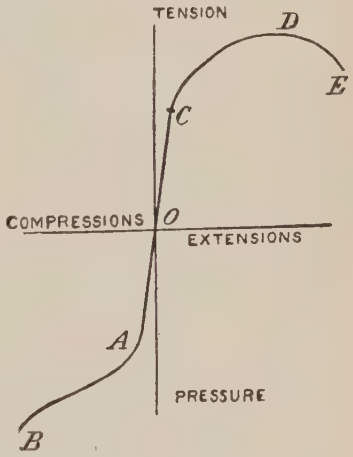


FIG. 39.

49. *The Elastic Limits for Normal Stress.*—The limit of elasticity is the stress at which the strains cease to be proportional to the stresses. If, for instance, small equal increments of tensile load are added and the elongations observed with a delicate extensometer, the elastic limit in

tension is the stress at which the first differences of the extensions cease to be constant and begin to increase. It appears also to be the point at which permanent set begins. In the first loading of a bar to near to the elastic limit, very small sets are often observed at stresses within the elastic limit, but these are probably due to straightening of the bar, to settlement of the bar in the grips, or small defects. It is usual in determining the elastic limit, to load a bar once or twice to a stress approaching the elastic limit before taking observations to determine it.

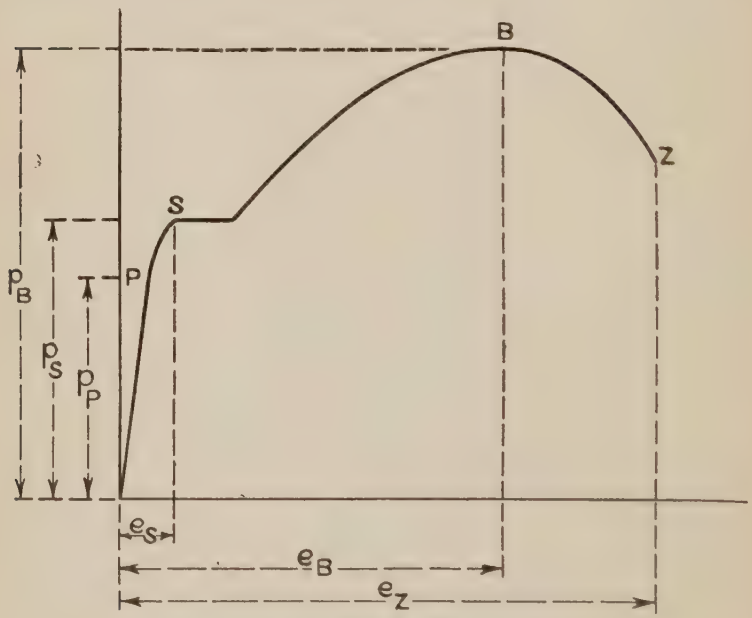


Fig. 40.

The elastic limit so found is the *primitive elastic limit*. As has been already stated, subjected to a series of cyclical variations of stress the elastic limits change in position. In some materials the primitive elastic limits are artificially raised by processes of manufacture, and if the bar is subjected to a range of stress, equal in tension and compression, and less than that between the primitive limits, the elastic range is found to have decreased, and the equal limits in tension and compression so established are termed the *natural elastic limits*. By cyclical variations of stress, unequal in tension and compression, both limits may be raised, or both lowered.

The elastic limits can only be found by delicate and careful observations. Hence some practical engineers have proposed arbitrary definitions with a view of facilitating the determination of a stress which for practical purposes might be taken to be the elastic limit. The elastic limit has been defined as the greatest stress at which there is no measurable permanent set, but this point depends on the delicacy of the measuring instrument and can only be determined by repeatedly unloading a bar, which is objectionable. It has been defined as the load at which the permanent set is

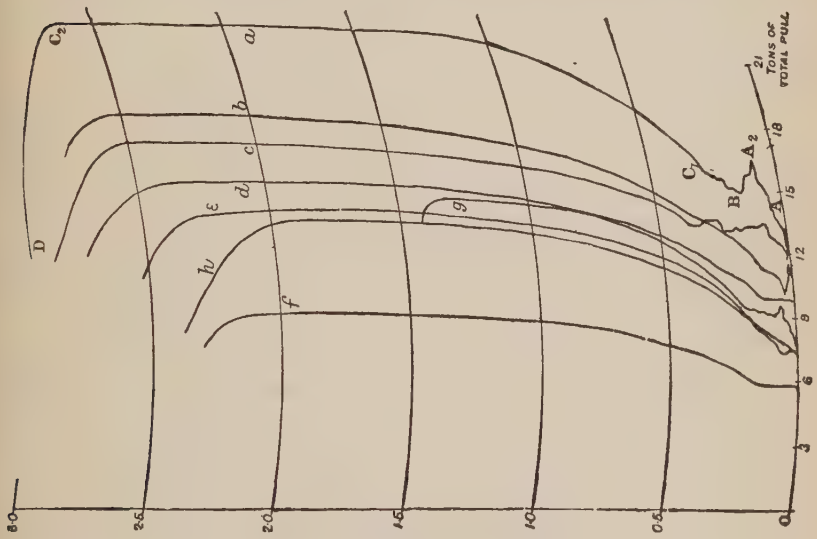


FIG. 41.—EXTENSIONS IN INCHES.

$\frac{3}{200}$ths of the gauge length, which is arbitrary and open to the same objections. It has been defined as the stress at which the rate of elongation is 50 per cent. greater than for moderate loads. But such a point has no significance.

50. *The Yield Point.*—In those materials which have a well-marked yield point, it can be detected with most testing-machines by a marked drop of the lever at the moment when it is reached. It is rather more accurately determined by holding dividers, with one leg in a slight punch mark, and describing a circle with the other before the load is applied. Then the load at which the dividers show the first distinct stretch is the yield point. In the short test specimens used for forgings this method fails. Then collars

are turned on the test piece and a gauge is set to the distance between them. The gauge is then lengthened by about one per cent. of its length. The yield point is then taken to be the load at which the lengthened gauge will just enter between the collars.

The phenomenon of yielding in a tension test bar appears to begin at some point of the bar and to progress gradually along the bar. It is due to the deformation of crystalline molecules by slips at the cleavage planes of the crystals.

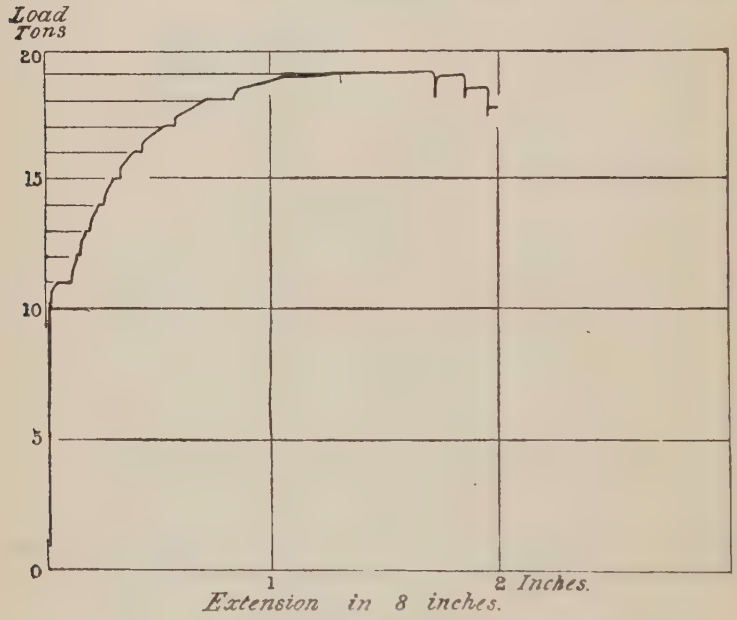


FIG. 42.

The yield point is raised and becomes less well marked by overstraining or straining beyond the primitive yield point.

51. *Form of the Stress-strain Curve at the Yield Point.*— The form of the stress-strain curve near the yield point is very variable, being greatly affected by extremely small stress differences and by differences in the time rate of extension. Further, in most autographic arrangements the record of stress is affected, when the specimen is yielding rapidly, by the inertia of the load. In Professor Kennedy's autographic apparatus the effect of the inertia of the load is eliminated, and fig. 41 gives some autographic diagrams taken in this apparatus. It is difficult to believe, however,

that the irregular curves near the yield point are not due to time differences, or to small stress differences arising out of the inertia of the elastic system formed by the test bar and testing-machine.[1]

52. *Local Drawing Out or Local Contraction.*—A bar or plate of ductile material such as soft steel is placed in the testing-machine and subjected to a gradually increasing stress till it is broken. At first, as the extensions are small, it is easy to keep the lever of the testing-machine floating with almost any rate of loading. At the yield point, however, the stretching suddenly becomes rapid, and with most testing-machines it is not possible to keep the lever floating. The

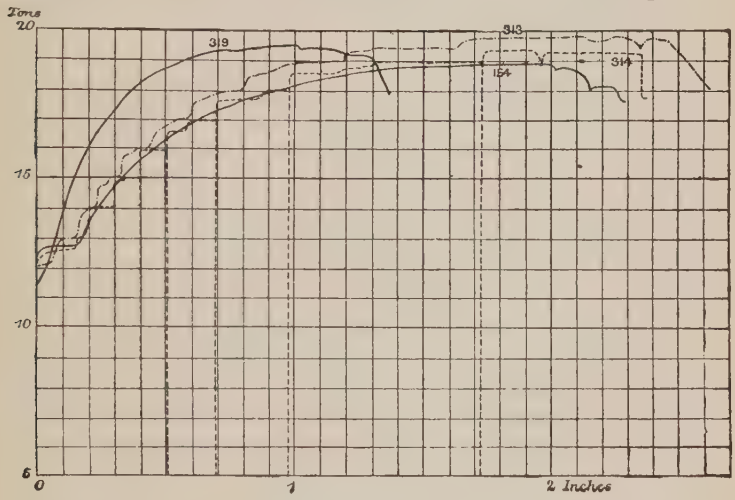


FIG. 43.

lever can only be kept floating if the pumps which work the hydraulic press are capable of moving the press ram as rapidly as the rate of increase of stretch. When the rapid stretch at the yielding point is ended, and the bar has again become capable of supporting an additional stress, it is quite easy, in general, to adjust the rate of loading so that the press just takes up the stretch and the lever remains floating almost without movement. And this continues till the maximum load is reached. Beyond that point the drawing out of the specimen at a restricted portion of its length begins, and

[1] In Professor Kennedy's diagrams the ordinates are curved:—*a* is a diagram for a Swedish iron bar; *b*, Shelton bar iron; *c*, Swedish iron; *d*, Landore rivet steel; *e* and *f*, Landore steel plate; *g*, cast steel; *h*, mild steel bar.

the reduction of area is so rapid that the stress must be diminished. It is here again difficult to keep the lever always floating. Finally, the bar breaks suddenly with a load considerably less than the maximum load it was sustaining just before the local drawing out commenced.

53. *Influence of Time on the Stress-strain Curve.*—It has been seen that the plastic yielding is gradual, either increasing indefinitely or at a diminishing rate under a given stress. Hence it might be expected that the plastic part of the stress-strain curve would be flatter the slower the rate of loading. In the same way, in taking autographic stress-strain diagrams, there is a notch in the diagram at any pause in the increase of loading. Fig. 42 shows a diagram for a manganese steel bar, tested with a pause of five minutes at each successive ton.

Fig. 43 shows the stress-strain curves for four pieces of wrought iron cut from the same bar. For bar 319 the extensions were measured on a length of 4½ inches; for the other bars on a length of 9 inches. In the case of bars 319 and 154 the extension increased at a nearly uniform rate during the plastic stage. In the case of bar 313 there were four-minute pauses at each successive ton, and the diagram is notched. In the case of bar 314 the load was taken off, and a pause of six minutes allowed at each successive ton. It may be noticed that the breaking-down point is more marked with the longer bars. The following table gives a summary of the tests:

No. of bar	Tons per sq. in.		Elongation per cent.
	Yield point	Maximum load	
319	12·97	22·19	34·7
154	14·37	22·10	25·8
313	13·68	22·34	29·5
314	14·23	22·47	28·2

54. *Correction of the Stress-strain Diagram to show the Actual Stress in the Bar.*—In ordinary stress-strain diagrams the loads are plotted as ordinates and the elongations of the bar, between two gauge points initially marked on the bar, as abscissæ. By a mere alteration of vertical scale, the ordinates represent equally the stress per sq. in. of the initial section of the bar.

Thus, in fig. 44, $O\,a$ represents the elongation $l\,\lambda$ in l inches length of bar, which has extended λ per inch when

the load is that represented by $a\,b$. If the bar is ω sq. ins. section, $a\,b$ will measure on a scale ω times that for the loads the stress per sq. in. of initial section of the bar. Up to the yield point the section of the bar changes very little, but beyond the yield point the deformation is so large that the section sensibly changes. Then $a\,b$ does not represent the stress per sq. in. of the actual section of the bar at the moment. To find this it is approximate enough to consider

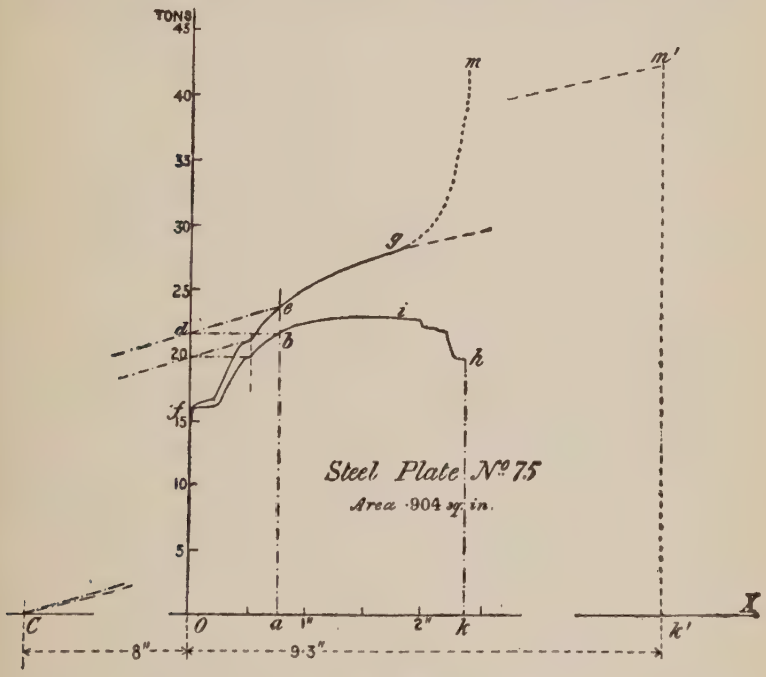


FIG. 44.

that the change of density is small compared with the deformation. Hence, so long as the deformation is general over the marked length of bar, that is, up to the maximum load point i, the section of the bar can be found from the measured length.

Let $l\,\omega$ be the length between gauge-points and section of the bar initially, and $l\,(1+\lambda)$ and ω_1 the length and section when the load is P. Then—

$$\omega\,l = \omega_1\,l\,(1+\lambda),$$
$$\omega_1 = \omega\,/\,(1+\lambda).$$

If $p = P/\omega$, the stress reckoned on the initial section, then the real stress on the actual section is—

$$p_1 = P/\omega_1 = p\,(1 + \lambda).$$

In the diagram take $o\,c = l$ to the same scale as that on which $o\,a = l\,\lambda$. Draw $b\,d$ horizontal. Through d draw $c\,d\,e$, cutting $a\,b$ in e. Then $a\,e$ represents p_1, the actual stress on the reduced section, to the same scale as that on which $a\,b$ represents p, the stress calculated on the initial section. If several points are thus found we get a curve $f\,e\,g$, lying above the ordinary stress-strain curve and extending to the point of maximum load. This is sometimes called the curve of true cohesive strength. It is simply a curve giving the relation of the actual stress and strain.

Beyond the point of maximum stress the construction fails, for the extension becomes chiefly local, and the l in the formula above is no longer the length between the gauge points. But another point in the curve may still be found. If the contracted section is measured after the bar is broken, then the breaking load $h\,k$ divided by that section gives the real stress $k\,m$ at the moment of fracture. It is obvious, however, that the part $g\,m$ of the curve is distorted, for while abscissæ up to the point i represent extensions of a fixed length l, the abscissæ from i to h represent extensions of an undetermined portion of l. The real elongation per unit of length at the moment of fracture in the part which is drawing out is given by the equation—

$$\lambda_1 = \frac{\omega - \omega_1}{\omega_1};$$

and if $O\,k'$ is taken equal to $l\,\lambda_1$, and $k'\,m'$ set off equal to $k\,m$, the general form $g\,m'$ of the final portion of the real stress-strain curve is determined. It is quite possible to measure the contracted section at intermediate loads between i and h during testing and to calculate intermediate points along $g\,m'$. So far as can be judged from one or two instances, the portion $g\,m'$ of the curve shows a regular increase of tenacity with increasing strain without the abrupt inflection of the distorted curve $g\,m$.

55. *Compressive Stress-strain Diagrams for nearly Plastic Materials.*—When very ductile materials are loaded with pressures which approach or reach the pressure of fluidity, the

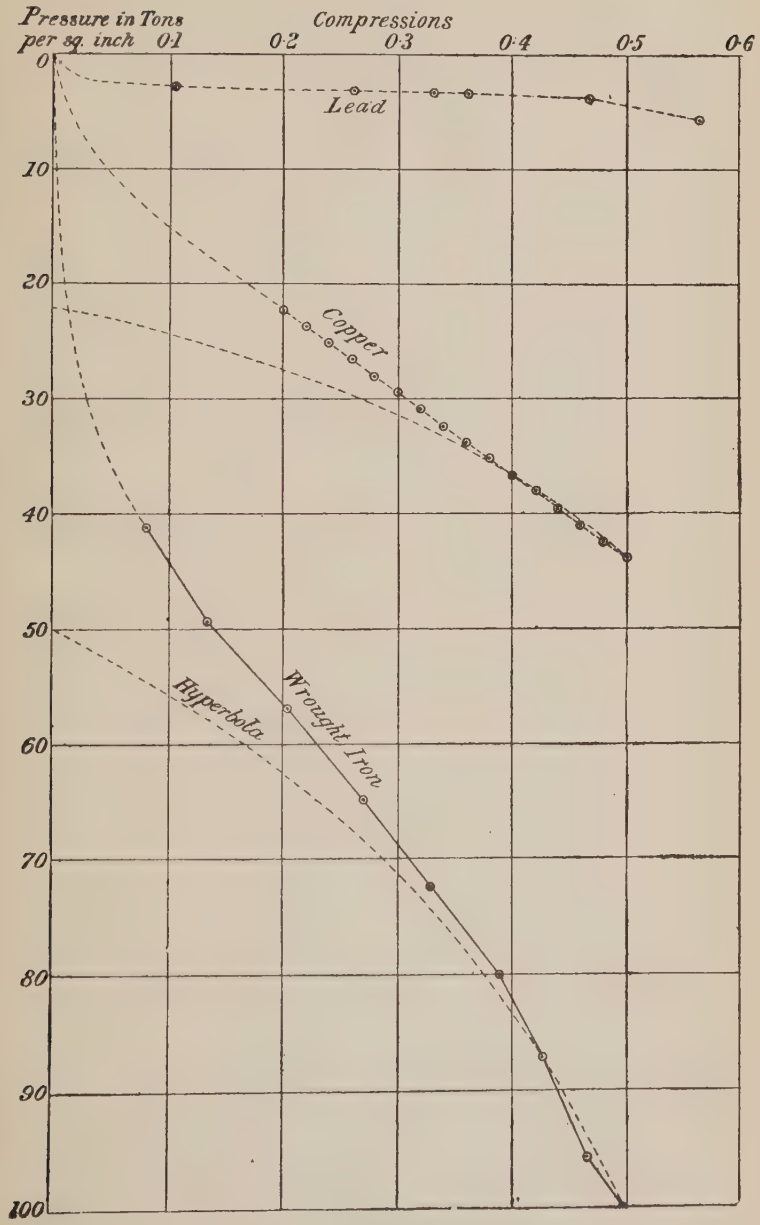

Pressure in Tons per sq. inch
Compressions
0·1
0·2
0·3
0·4
0·5
0·6
0
10
20
30
40
50
60
70
80
90
100
Lead
Copper
Wrought Iron
Hyperbola

FIG. 45.

strains follow approximately the plastic law, and the stress-and-strain curve becomes nearly a hyperbola.

In tension experiments a difficulty arises from the extension becoming local instead of general. It is impossible after local contraction sets in to determine what length of bar is being elongated, and hence the strain per unit length cannot be determined. In compression experiments this difficulty does not arise. But, on the other hand, it is difficult to keep long bars straight during compression, and hence experiments must be made on short cylinders, for which accurate measurements are more difficult. Besides this, in short cylinders a barrel-shaped distortion occurs, due partly, no doubt, to friction at the ends against the plates which apply the pressure. Nevertheless, these results are interesting as showing an approach to a perfectly plastic condition. Fig. 45 shows the stress-strain curves for short cylinders of lead, copper, and wrought iron.[1] The lead cylinder was initially 50·05 mm. diameter and 64·4 mm. in height. The following table gives the loads and compressions:

Crushing of a Lead Cylinder (Kick)

Load in tons	Height in inches	Compression in inches	Diameter at centre in inches	Stress, in tons per sq. in. of central area
—	2·576	—	2·00	—
2·9	2·312	·264	2·16	·79
3·25	1·904	·672	2·40	·72
3·35	1·716	·860	2·52	·67
3·45	1·636	·930	2·60	·65
3·95	1·376	1·200	2·84	·62
5·65	1·128	1·448	3·16	·72

It appears that the pressure of fluidity was reached at about 0·75 tons per sq. in., and the stress remained approximately constant, notwithstanding the large deformation. Fig. 45 shows a similar curve for a wrought-iron cylinder.

Fig. 46 gives load-strain and stress-strain curves for cylinders of various metals. The stresses are calculated from the loads by the formula $p = \text{P}\ (1 - \lambda)\ /\omega$.

56. *Plastic Compression of Copper Cylinders.*—Small copper cylinders, made of the softest and purest copper, are used in crusher gauges for determining the powder pressure

[1] *Proc. Inst. of Civil Engineers*, vol. i. p. 188. The lead curve is plotted with loads on specimen as ordinates, not stress per sq. in.

in the bore of guns. The copper cylinders are made in two sizes, 1 sq. in. and $\frac{1}{12}$ sq. in. in section, and the initial length

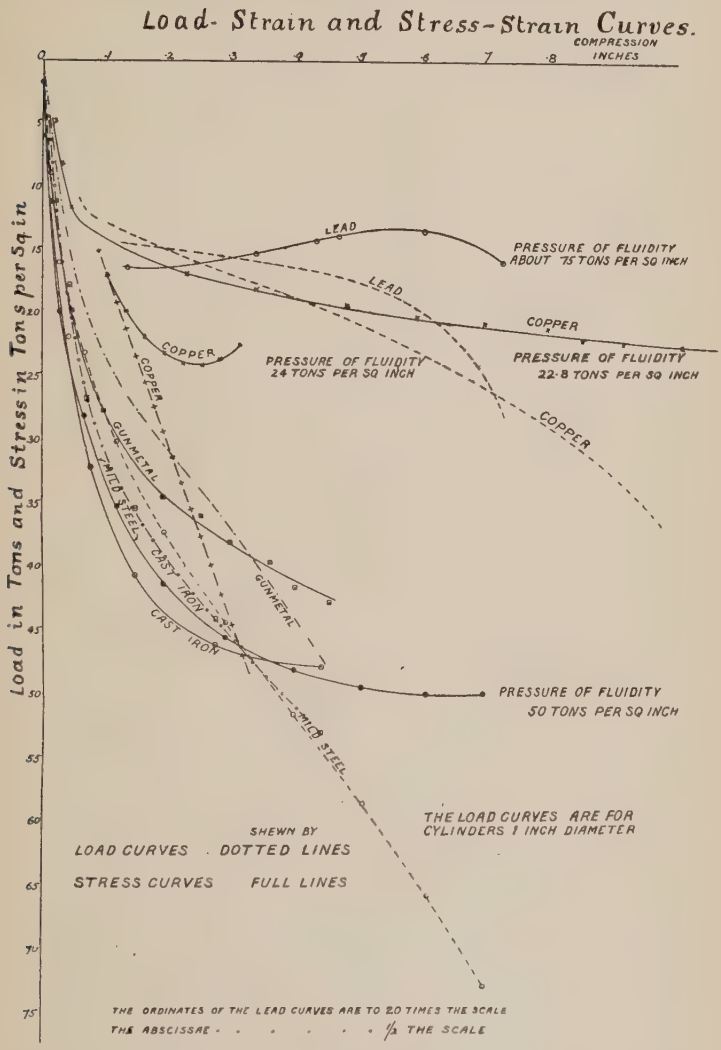

Load- Strain and Stress-Strain Curves.
COMPRESSION INCHES
Load in Tons and Stress in Tons per Sq in
LEAD
PRESSURE OF FLUIDITY ABOUT 75 TONS PER SQ INCH
LEAD
COPPER
COPPER
PRESSURE OF FLUIDITY 24 TONS PER SQ INCH
PRESSURE OF FLUIDITY 22·8 TONS PER SQ INCH
COPPER
COPPER
GUNMETAL
MILD STEEL
CAST IRON
GUNMETAL
CAST IRON
PRESSURE OF FLUIDITY 50 TONS PER SQ INCH
MILD STEEL
SHEWN BY
LOAD CURVES . DOTTED LINES
STRESS CURVES FULL LINES
THE LOAD CURVES ARE FOR CYLINDERS 1 INCH DIAMETER
THE ORDINATES OF THE LEAD CURVES ARE TO 2·0 TIMES THE SCALE
THE ABSCISSAE . . . . . ½ THE SCALE

Fig. 46.

is 0·5 inch. Tables have been published[1] giving the compression of these cylinders when compressed by hydraulic

[1] *Treatise on Service Ordnance*, 1893, p. 530.

Compression of Soft Copper Cylinders

Cylinder initially 0·5 in. long and $\frac{1}{2\cdot4}$ sq. in. area				Cylinder initially 0·5 in. long and $\frac{1}{1\cdot2}$ sq. in. area			
Compression in inches $l\lambda$	Compressed length in inches $l(1-\lambda)$	Pressure in lbs. P	Pressure per sq. in. of compressed area, in tons	Compression in inches $l\lambda$	Compressed length in inches $l(1-\lambda)$	Pressure in lbs. P	Pressure per sq. in. of compressed area, in tons
·10	·40	2,091	17·9	·10	·40	4,000	17·1
·11	·39	2,225	18·7	·11	·39	4,333	18·1
·12	·38	2,359	19·3	·12	·38	4,666	19·0
·13	·37	2,494	19·8	·13	·37	5,000	19·8
·14	·36	2,628	20·3	·14	·36	5,333	20·5
·15	·35	2,763	20·7	·15	·35	5,666	21·2
·16	·34	2,897	21·1	·16	·34	6,000	21·8
·17	·33	3,031	21·4	·17	·33	6,333	22·3
·18	·32	3,162	21·6	·18	·32	6,666	22·8
·19	·31	3,296	21·9	·19	·31	7,000	23·2
·20	·30	3,431	22·1	·20	·30	7,333	23·5
·21	·29	3,565	22·2	·21	·29	7,666	23·8
·22	·28	3,700	22·2	·22	·28	8,000	23·9
·23	·27	3,834	22·1	·23	·27	8,333	24·0
·24	·26	3,968	22·1	·24	·26	8,666	24·0
·25	·25	4,103	22·0	·25	·25	9,000	24·0
				·26	·24	9,333	24·0
				·27	·23	9,666	23·7
				·28	·22	10,000	23·5
				·29	·21	10,333	23·2
				·30	·20	10,666	22·8
				·31	·19	11,000	22·4

pressure, the compressions being measured by a Whitworth measuring machine.

The table on the preceding page gives the compressions $l\ \lambda$, compressed length $l\ (1 - \lambda)$, and observed pressure producing the compression. Neglecting the barrel-shaped distortion the stress reckoned on the deformed prism is—

$$p_1 = P\ (1 - \lambda)\ /\omega$$

and the values of this have been calculated and placed in the tables.

It will be seen that for compressions exceeding two-fifths of the original length the pressure on the actual deformed section is nearly constant. Further, the numbers for the cylinder of $\frac{1}{1\frac{1}{2}}$ sq. in. area are almost exactly double those for the cylinder $\frac{1}{2\frac{1}{4}}$ sq. in. area. According to both tables the pressure of fluidity for soft copper must be about 22 tons per sq. in.[1]

The following are similar results on larger cylinders from tests made by the author :

Compression of a Short Copper Cylinder

Diameter, 1·092 in.; area, 0·936 sq. in.; height, 2·129 in.

Load, tons P	Height, inches	Compression, inches $l\ \lambda$	Stress on compressed area, in tons per sq. in. p_1
10	2·109	·020	10·58
15	2·101	·028	15·81
20	1·950	·179	19·56
25	1·691	·438	21·20
30	1·478	·651	22·24
35	1·297	·832	22·77
40	1·146	·983	22·99
45	1·031	1·098	23·27
50	0·939	1·190	23·55

This was a piece of ordinary copper rod of much larger area than the test specimens in the preceding table.

Pure Aluminium

Diameter, 0·835 in.; area, 0·5478 sq. in.; height, 1·676 in.

Load, tons	Height, inches	Compression, inches	Stress on compressed area in tons per sq. in.
4	1·56	·12	6·82
6	1·26	·42	8·26
8	1·06	·62	9·27
10	0·91	·77	9·95
12	0·78	·90	10·23
14	0·70	·98	10·71

[1] *Treatise on the Manufacture of Guns* (official), p. 92.

57. *Raising the Elastic Limit by Stress.*—For iron, steel, and other metals a load exceeding the elastic limit raises that limit. Thus Bauschinger gives the following results of experiments on five gun-metal bars, of a section about 2·8 × 0·5 inches. The elongations were measured in 8 inches by the mirror apparatus:

No. of bar	Original elastic limit in tons per sq. in.	Stress applied in tons per sq. in.	Permanent set, inches	Raised elastic limit in tons per sq. in.	Tenacity in tons per sq. in.
1	4·62	6·56	·00061	6·15	14·2
2	3·82	6·10	·00061	5·74	14·9
3	3·84	6·56	·00067	5·77	13·3
4	3·50	5·85	·00054	5·80	12·9
5	3·77	6·02	·00057	5·66	13·2

In these experiments the second loading was effected only a few minutes after the first loading.

Bauschinger noticed that if a bar after loading beyond the elastic limit was left for twenty-four hours or more at rest it recovered partially the set previously taken, and if then the elastic limit was again determined it was in some cases raised not only up to but beyond the load previously applied. If the bar is heated even to the temperature of boiling water the recovery is more rapid and complete.

Fig. 47 shows a stress-strain diagram of a piece of steel plate, taken autographically. The yielding point or breaking-down point is strongly marked at a load of about 18 tons. At 19 tons, 21 tons, and 23 tons the load was almost completely removed, the pencil tracing downwards and retracing upwards almost exactly straight lines, parallel to the primitive elastic line. Thus, at 19 tons the pencil described while the load was removed and replaced the straight line $a\ b$. The distance $o\ b$ represents the permanent set produced by the load of 19 tons, and the stress-strain diagram for the material altered by loading is the line $b\ a\ c\ \ldots$ Similarly for the other points at which the load was removed. The peculiarity specially to be noted, and which indeed is only shown in such autographic diagrams as this, is the steepness and almost straightness of the curve at $a\ f$. The material is not only nearly perfect in its elasticity in the reimposition of the load up to the point a, corresponding to a load of 19 tons, but is nearly perfect in elasticity to the point f, corresponding to a higher load. More accurately, f is a new yielding point in the material altered by loading.

58. *Work done in Stretching the Test Bar.*—If P is the load at any instant of a test and $d\,l$ the increment of length during a short period, in which P may be regarded as

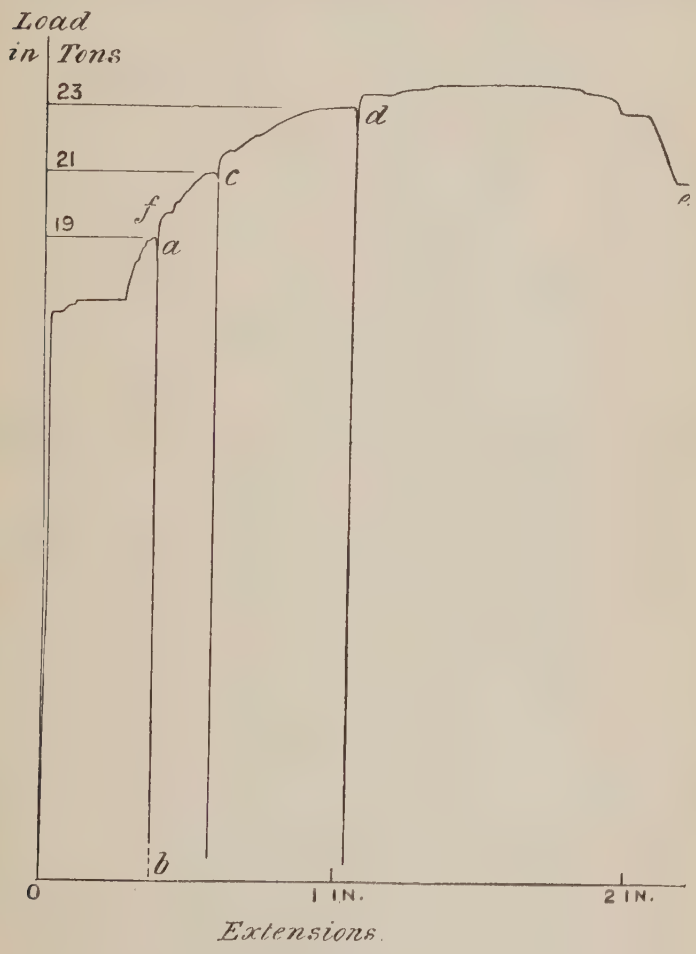


FIG. 47.

constant, P $d\,l$ is the work done on the bar. Hence the whole area of a load-strain diagram is the whole work done on the portion of the bar between the gauge points. Let a be the section and l the length of the bar between gauge points. Then $a\,l$ is the volume of the bar, the stretch of

which is represented on the diagram. Let A be the area of the diagram taken with a planimeter in sq. ins., and let the scales of the diagram be m inches to 1 ton of load and n inches to 1 inch of extension, then $m\,n$ sq. ins. represent on the diagram 1 inch-ton. Hence the work on the stretched length of bar is $A/m\,n$ inch-tons, and the work reckoned per cubic inch is—

$$U = \frac{A}{m\,n\,a\,l}$$

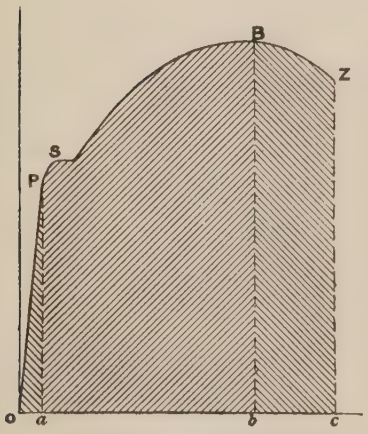


Fig. 48.

The total work consists of three parts (fig. 48): O a P is the work done during the elastic period; a P B b the work during the general extension of the bar; b B Z c the work during the local drawing out. For metals O a P is small, b B Z c is zero for such metals as cast iron and many alloys which break at maximum load. The work up to the point at which local drawing begins is O P S B b.

The part b B Z c is a distorted part of the diagram and generally not well determined. The elongations during drawing out are elongations of a short part of the bar only. It is desirable to discard this part of the diagram and to reckon the work up to maximum load only, that is, the area O S B b.

59. *Diagram Factor.*—Let $p_{max.}$ be the stress per sq. in. at maximum load and $\lambda_{max.}$ the corresponding elongation per inch length. The ratio D of the area O S B b to its enclosing rectangle is nearly constant for a given material, and may be termed a *diagram factor*. Its value for mild steel is about 0·85. Hence the work expended in deformation up to maximum load may be calculated approximately without an autograph diagram. Its value is—

$$D\,p_{max.}\,\lambda_{max.} \text{ tons per cubic in.}$$

CHAPTER IV

ELONGATION AND CONTRACTION OF AREA

60. *Commercial Measures of Ductility.*—In the case specially of wrought iron and mild steel, so widely used in construction, it is of great importance that there should be accepted tests of ductility. Such materials have to be subjected to rough usage in the workshop, to shearing, bending, forging, &c., and, if not sufficiently tough, they are liable to crack and to cause serious delay and difficulty. There are rough but valuable workshop tests known as bend, temper, and punching tests, which give much information. But the most general measure of the ductile quality of a material is the ultimate extension or contraction of area in a tension test.

Suppose a tension test bar ruled with straight lines at right angles to the direction of the stress. As the bar stretches, the distance between these lines increases, but, so far as can be judged, they remain straight and parallel during the increase of stress till the maximum load is reached. During the local drawing out the lines become curved in the part which is drawing out. It has been inferred from this curvature of the lines that the stress becomes very ununiform on the section of fracture, being greatest at the centre of the bar. Some slight variation of stress probably is produced, but it is very doubtful if the variation is at all large.

Fig. 49 is from photographs of a strip of mild steel plate taken during the process of testing. A was taken just when the maximum load was on the bar. No beginning of the drawing out is visible, and the lines drawn on the bar are still straight, as far as can be observed. B was taken just after the drawing out became visible, and when the stress on the bar had been a little diminished. At the centre of the part drawn out the line is still accurately straight, but the

lines on each side are curved. C was taken at the very moment before fracture. D is the bar after fracture.

From what has been stated it may be inferred that up to the maximum load, and except near the enlarged ends of the bar, the stretch is approximately uniformly distributed along the bar, the percentage of elongation is therefore independent of the gauge length in which it is measured. It is otherwise after drawing out has commenced.

61. *Distribution of Elongation along the Bar.*—If a bar is divided into short lengths before testing, and these are measured again after the bar is broken, the plastic extension in each length will be determined. It will be found that the amount of extension is more or less irregular along the bar. In the inch length in which local contraction and fracture occur the extension is very great. On either side it diminishes, at first rapidly, afterwards more slowly, and is least near the enlarged ends at which the specimen is held. But there are irregularities, showing that there are differences of plasticity along the bar, and in rare cases two local contractions form at different parts of the length.

The following table gives measured values of the elongation for various materials in consecutive one-inch lengths along the test bars:

ELONGATIONS IN 1-INCH LENGTHS OF BAR AT DIFFERENT DISTANCES FROM THE FRACTURE

(The elongation in the division in which fracture occurred is indicated in italic type.)

Material	Inches along the bar											
	1	2	3	4	5	6	7	8	9	10	11	12
Lead	0·18	·15	·30	·17	·14	·22	·16	·17	*1·01*	—	—	—
Brass	0·23	·20	·20	*·30*	·21	·22	·24	·21	·21	·21	—	—
Wrought iron:												
Angle iron	0·05	·06	·06	·06	·06	·065	·07	·08	*·135*	·08	—	—
Channel iron	0·09	·11	·08	·10	*·23*	·14	·11	·10	·10	·09	—	—
Rivet iron	0·17	·195	·23	*·51*	·26	·23	·25	·23	·23	·18	—	—
Square bar	0·24	·22	·22	·22	·21	·27	*·50*	*·50*	·26	·18	·17	·17
Flat bar	0·11	*·16*	·14	·10	·10	·10	·10	·10	·10	—	—	—
Steel:												
Steel plate	*0·70*	·30	·22	·19	·19	·15	·15	·16	—	—	—	—
Steel axle	0·16	·17	·21	·21	·18	·17	·21	*·65*	·46	·17	·13	·10
Steel tyre	0·02	·06	·08	·21	*·67*	·22	·05	·02	·03	·06	·08	·12

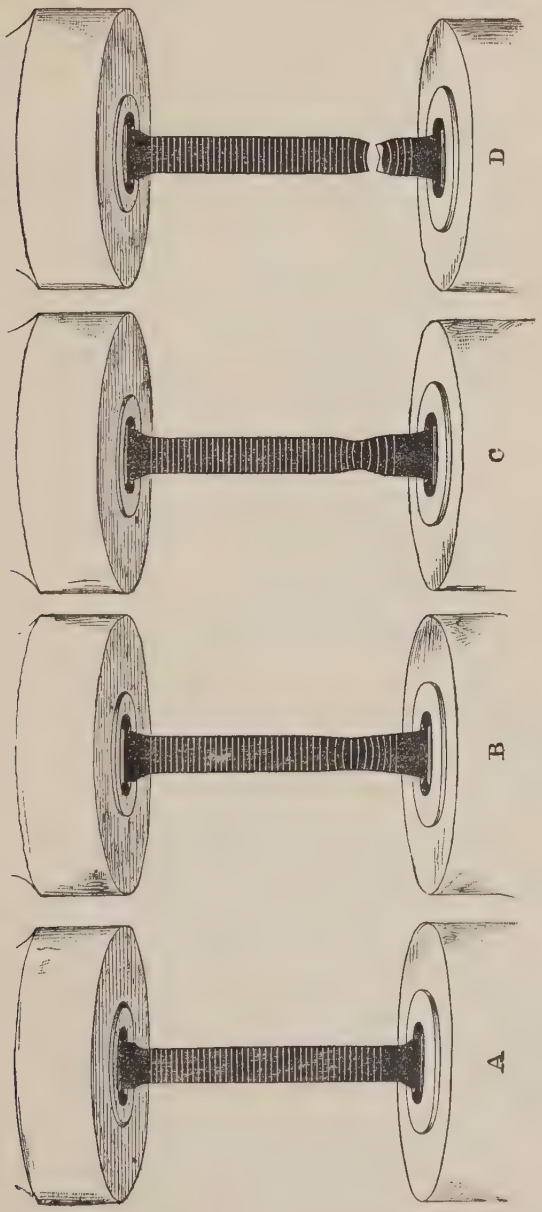


FIG. 49.—DRAWING OUT OF MILD STEEL.

A good idea of the distribution of drawing out along the bar is obtained by plotting the extensions per inch as ordinates at the centre of each inch length, and connecting the points by a curve. Fig. 50 shows some results so plotted.

As the rate of elongation varies along the bar the percentage of elongation is different for different gauge-lengths. In different gauge-lengths, including the fracture, the percentage of elongation is less the longer the gauge-length.

When the extensions in consecutive inch or half-inch lengths are measured, it is possible to calculate the percentage of elongation with the fracture at the centre of the gauge-length, and this is desirable in tests for strictly comparative purposes. Thus the ultimate extension of the rivet-iron bar above in a length of 10 ins. is best obtained thus—

Extension in fourth inch (fracture)	0·51
„ divisions 1, 2, 3, 5, 6, 7	1·335
Double extension in division 8	0·46
Extension in division 9	0·23
„ ten inches symmetrical with fracture . .	2·535

Elongation per cent., 25·35

In ordinary commercial testing, the gauge-length is marked on the bar before testing, and so long as the fracture occurs within the gauge-length the measure of elongation is accepted as satisfactory. It is sometimes prescribed that, if the fracture is outside the middle half of the gauge-length, a new test may be made at the option of the manufacturer.

62. *Variation of Elongation with Gauge-length.*—The following table contains the results of some tests, part of a larger series made for the Standards Committee on steel boiler-plates of a tenacity from 27 to 29 tons per square inch.[1] The test bars were exceptionally long, the plate thickness $\frac{5}{8}$ to $1\frac{1}{4}$ inch, and the extensions were measured in consecutive half-inch lengths along the test bars.

[1] Unwin, 'Tensile Tests,' *Proc. Inst. Civil Engineers*, clv.

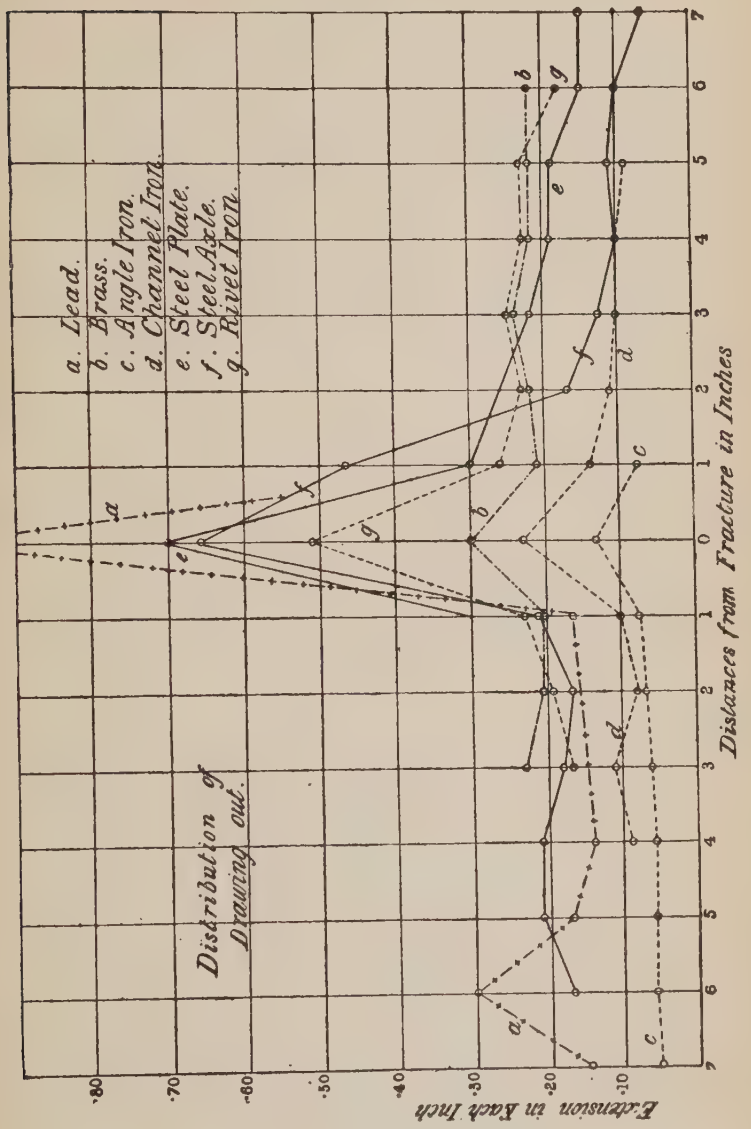

a. Lead.
b. Brass.
c. Angle Iron.
d. Channel Iron.
e. Steel Plate.
f. Steel Axle.
g. Rivet Iron.
Distribution of Drawing out.
Extension in Each Inch
Distances from Fracture in Inches
·80
·70
·60
·50
·40
·30
·20
·10
0
1
2
3
4
5
6
7

FIG. 50.

STEEL BOILER-PLATES

EXTENSIONS IN EACH HALF-INCH

Test No.	2386	2387	2388	2389	2390	2391	2392	2393	2394	2395	2396	2397
Area	1·2931	1·2976	1·2779	1·2767	1·3159	1·3270	1·3368	1·2390	0·9327	0·9756	0·9502	0·9812
18	—	—	0·08	0·06	0·08	0·07	0·06	0·08	0·105	0·07	0·095	0·08
17	—	—	0·08	0·05	0·08	0·07	0·06	0·065	0·11	0·11	0·10	0·075
16	—	—	0·075	0·06	0·10	0·06	0·07	0·08	0·115	0·10	0·105	0·085
15	—	—	0·06	0·06	0·11	0·07	0·08	0·07	0·115	0·09	0·11	0·075
14	0·06	0·08	0·06	0·06	0·11	0·08	0·07	0·075	0·105	0·10	0·11	0·085
13	0·08	0·105	0·06	0·045	0·10	0·075	0·06	0·08	0·095	0·10	0·10	0·085
12	0·095	0·105	0·05	0·05	0·10	0·085	0·07	0·065	0·09	0·11	0·09	0·08
11	0·095	0·105	0·07	0·05	0·10	0·08	0·08	0·075	0·08	0·10	0·095	0·075
10	0·09	0·130	0·07	0·06	0·085	0·09	0·08	0·08	0·08	0·10	0·085	0·08
9	0·09	0·125	0·07	0·055	0·09	0·10	0·07	0·07	0·08	0·10	0·095	0·09
8	0·10	0·14	0·07	0·07	0·095	0·095	0·08	0·08	0·085	0·10	0·10	0·10
7	0·105	0·13	0·08	0·07	0·09	0·110	0·08	0·11	0·085	0·11	0·105	0·10
6	0·11	0·11	0·07	0·06	0·09	0·115	0·08	0·10	0·09	0·11	0·11	0·115
5	0·13	0·12	0·08	0·065	0·10	0·13	0·09	0·10	0·08	0·11	0·11	0·11
4	0·135	0·11	0·07	0·06	0·10	0·14	0·10	0·10	0·09	0·12	0·11	0·11
3	0·145	0·12	0·08	0·07	0·11	0·14	0·11	0·12	0·11	0·12	0·11	0·125
2	0·155	0·14	0·11	0·07	0·12	0·16	0·11	0·14	0·11	0·13	0·12	0·16
1	0·20	0·19	0·145	0·08	0·24	0·24	0·16	0·27	0·16	0·17	0·17	0·30
Fracture	0·40	0·37	0·16	0·11	0·42	0·48	0·29	0·48	0·35	0·44	0·41	0·32
1	0·24	0·21	0·09	0·08	0·19	0·19	0·255	0·16	0·30	0·28	0·24	0·16
2	0·16	0·15	0·09	0·07	0·11	0·14	0·165	0·12	0·13	0·15	0·14	0·12
3	0·12	0·13	0·09	0·06	0·09	0·12	0·11	0·07	0·12	0·12	0·125	0·11
4	0·115	0·12	0·08	0·05	—	0·11	0·11	—	0·11	0·12	0·105	0·11
5	0·105	0·13	0·07	0·06	—	0·10	0·09	—	0·06	0·11	0·09	0·12
6	0·09	0·12	0·06	0·06	—	0·09	0·09	—	—	0·11	0·08	0·12
7	0·09	0·12	—	0·04	—	0·08	0·095	—	—	0·11	—	0·11
8	0·07	0·11	—	—	—	—	0·085	—	—	0·10	—	—
9	0·07	0·11	—	—	—	—	—	—	—	—	—	—
10	0·07	0·10	—	—	—	—	—	—	—	—	—	—
11	0·07	0·10	—	—	—	—	—	—	—	—	—	—
12	0·07	0·07	—	—	—	—	—	—	—	—	—	—

From these measurements the following percentages of elongation in different gauge-lengths have been calculated by the method described so that they are elongations with fracture at the centre of the gauge-length.

PER CENT. OF ELONGATION IN DIFFERENT GAUGE-LENGTHS.

FRACTURE IN MIDDLE OF GAUGE-LENGTH.

No. of Test Bar.	2386	2387	2390	2391	2394	2395
Cut Lengthways of Plate.						
In 2 ins. . . .	49·9	45·8	48·3	53·0	46·5	51·5
„ 4 „ . . .	38·6	35·6	34·5	39·9	34·5	38·2
„ 6 „ . . .	33·4	31·7	29·5	34·2	28·9	33·0
„ 8 „ . . .	29·8	29·9	26·9	30·5	25·9	30·1
„ 10 „ . . .	27·1	28·7	25·0	28·2	24·0	28·1
„ 12 „ . . .	25·3	27·3	24·0	26·3	22·7	26·8
„ 14 „ . . .	23·8	26·1	23·5	24·8	22·3	25·9
„ 16 „ . . .	—	—	23·3	23·5	22·3	25·1
„ 18 „ . . .	—	—	22·5	22·3	—	—

No. of Test Bar.	2388	2389	2392	2393	2396	2397
Cut Across the Plate.						
In 2 ins. . . .	24·8	17·0	42·1	52·0	47·5	46·0
„ 4 „ . . .	21·0	14·9	32·6	36·5	35·6	35·1
„ 6 „ . . .	18·9	13·9	27·9	31·0	30·2	31·0
„ 8 „ . . .	17·8	13·8	26·5	28·3	27·6	28·6
„ 10 „ . . .	17·1	13·5	23·2	25·6	25·8	26·5
„ 12 „ . . .	16·4	13·0	21·9	23·8	24·6	24·6
„ 14 „ . . .	15·7	12·5	20·6	22·5	23·9	23·5
„ 16 „ . . .	15·3	12·5	19·9	21·5	23·7	23·6
„ 18 „ . . .	15·4	12·3	19·1	20·8	—	—

63. *Influence of the Size of Test Bar on the Percentage of Elongation—Barba's Law.* Observation proves that two geometrically similar test bars deform similarly when fractured in a tensile test. Then the length of the part which contracts locally must depend on the section of the test bar, and the percentage of elongation is different for a given gauge-length in bars of different cross-sections. Let fig. 51 represent two similar test bars of the same material, the linear dimensions of one being n times those of the other. Then the lengths affected by local contraction are a and $a' = na$. The percentage of elongation reckoned on the whole length of the bars, the deformed bars being similar, is the same. But on any given gauge-length the percentage of elongation is greater for the larger bar, because of the greater extent of the local contraction.

The general law that similar test bars deform similarly

was first stated by M. J. Barba.[1] It follows that, for cylindrical test bars, the percentage of elongation is constant for a given material, if the ratio of gauge-length to diameter is constant. In plate test bars, not strictly geometrically similar, the percentage of elongation is practically constant, if the ratio of gauge-length to square root of cross-section is constant. The form of cross-section within somewhat wide limits, if the area is constant, does not appear to influence the elongation.

The following results of tests by M. Barba show that for a given gauge-length the percentage of elongation increases as the diameter of the test bar increases.

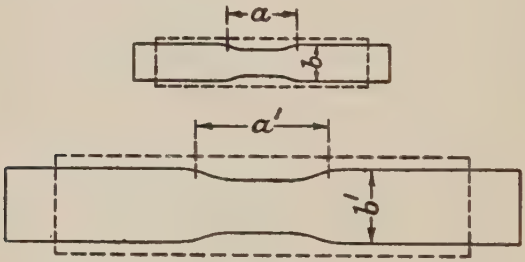


FIG. 51.

DIFFERENCES OF ELONGATION IN BARS WITH DIFFERENT PROPORTIONS OF LENGTH TO DIAMETER

(Pieces cut from bar of soft steel rolled to 1¼ in. diameter and annealed. Also on a harder steel.)

Diameter, inches	Length between gauge points in inches	$\frac{\text{Length}}{\text{Diameter}}$	Limit of elasticity, tons per sq. in.	Breaking stress, tons per sq. in.	Elongation per cent.
·787	3·94	5	15·85	23·47	37·5
·394	3·94	10	15·72	23·40	30·2
·197	3·94	20	16·00	23·85	25·0
·787	3·94	5	21·90	37·60	25·9
·394	3·94	10	21·25	37·67	21·0
·197	3·94	20	20·94	38·05	17·0

[1] 'Résistance des matériaux. Épreuves de résistance à la traction. Étude sur les allongements des métaux après rupture.' *Mémoires de la Société des Ingénieurs Civils*, 1880, Part I. p. 682.

The following table gives the mean of a large series of results of tests by the author on mild steel plates, the gauge-length 8 ins. and the sections of the test bars $\frac{1}{2}$ and 1 sq. in.:

DIFFERENCES OF ELONGATION IN 8 INCHES WITH TEST BARS OF DIFFERENT SECTION

SHIP-PLATES.			BOILER-PLATES.		
Thickness of plates	Mean elongation in 8 inches		Thickness of plates	Mean elongation in 8 inches	
	Bars of 0·5 sq. in. section	Bars of 1 sq. in. section		Bars of 0·5 sq. in. section	Bars of 1 sq. in. section
Inch	Per cent.	Per cent.	Inch	Per cent.	Per cent.
$\frac{1}{4}$	22·7	25·4	$\frac{1}{4}$	22·7	26·2
$\frac{3}{8}$	26·0	29·1	$\frac{3}{8}$	26·9	29·4
$\frac{5}{8}$	24·7	26·6	$\frac{5}{8}$	25·6	28·5
$\frac{7}{8}$	22·3	24·9	$\frac{7}{8}$	24·3	27·2
$1\frac{1}{4}$	19·8	22·6	$1\frac{1}{4}$	24·6	27·4
Mean of all	23·1	25·7	Mean of all	24·8	27·7

On the other hand in geometrically similar test bars, that is when the linear sectional dimensions and the gauge-length have a constant ratio, the percentage of elongation should be the same, and the following tests by M. Barba show that this is very approximately the case:

IDENTITY OF PERCENTAGE OF ELONGATION IN SIMILAR BARS

A billet of extra soft steel was hammered to an octagon of $3\frac{1}{4} \times 3\frac{1}{4}$ in., rolled to a bar $1\frac{1}{4}$ in. diameter and annealed. Three test pieces give the following results:

Diameter, inches	Length between gauge-points, inches	$\frac{\text{Length}}{\text{Diameter}}$	Limit of elasticity, tons per sq. in.	Breaking stress, tons per sq. in.	Elongation per cent.
·787	7·87	10	15·72	23·85	31·0
·394	3·94	10	15·68	23·35	31·5
·197	1·97	10	15·72	23·90	30·4
Means			15·71	23·70	31·0

EXPERIMENTS ON TWO HARDER QUALITIES OF STEEL, ROLLED TO BARS $1\frac{9}{16}$ IN. DIAMETER AND ANNEALED

Diameter, inches	Length between gauge points, inches	Length / Diam.	Limit of elasticity, tons per sq. in.	Breaking stress, tons per sq. in.	Contraction per cent.	Elongation per cent.
·272	1·97		15·22	26·77	69·3	32·8
·407	2·95		15·22	26·65	69·0	33·2
·543	3·94		15·34	26·70	69·7	33·0
·679	4·92	1 to	15·16	26·45	68·6	33·5
·815	5·91	7·24	15·10	26·40	69·2	33·6
·950	6·89		15·22	25·95	69·7	33·2
1·090	7·87		15·28	25·40	68·8	33·0
1·22	8·86		15·22	25·11	69·5	34·0
Means			15·22	26·20	69·2	33·3
·272	1·97		20·76	41·11	36·5	20·0
·407	2·95		23·21	41·20	38·0	18·8
·543	3·94		22·65	40·50	37·4	18·2
·679	4·92	1 to	24·10	40·17	38·4	18·1
·815	5·91	7·24	25·76	40·30	31·8	18·0
·950	6·89		24·16	39·34	35·8	18·1
1·090	7·87		24·16	40·10	34·4	19·5
1·22	8·86		—	—	—	—
Means			23·53	40·35	36·1	18·6

EXPERIMENTS ON PLATES

Dimensions of test bar		Width / Thickness	Length between gauge points, inches	Length / $\sqrt{\text{area}}$	Limit of elasticity, tons per sq. in.	Breaking stress, tons per sq. in.	Elongation per cent.
Width	Thickness						
·787	·197		1·97	5	10·67	23·60	39
1·575	·394	4 to 1	3·94	5	10·86	24·25	39
2·362	·591		5·91	5	13·14	24·70	39

The importance of the size of test piece is this. Strict limits of elongation are set out in specifications for material. But they are misleading if the size of test piece is disregarded. Thus for a $\frac{5}{8}$-inch boiler-plate the percentage of elongation would be 28·2 if the test piece were $1\frac{1}{2}$ inch wide; 29·5 if 2 inches wide; and 30·8 if $2\frac{1}{2}$ inches wide. The differences may not seem great, but they would be very important if the reception of material was in question.

64. *Contraction of Area at Fracture.* Let Ω be the initial cross-section of the test bar, Ω_1 the area of the fractured

section. Then $\omega = \Omega - \Omega_1$ is termed the contraction of area, and $100\ \omega / \Omega$ is the percentage of contraction. In the opinion of some engineers the percentage of contraction is a better indication of the ductility of a material than the percentage of elongation. It is, however, a quantity which cannot be measured so accurately as the extension. The fractured surface is often very irregular, and in the case of a section initially rectangular it is not a rectangle but has curved sides. The contraction is also much affected by small local defects.

Relation of Ultimate Elongation to Contraction of Area.— It is now common, in testing iron and steel by tension, to record the ultimate elongation in a length of 8 or 10 inches, and the contraction of area at fracture, as data useful for deciding on the value of a material. A good deal of confusion arises from the discrepancy between these two quantities.

It has already been shown (§ 26) that for a perfectly plastic material, if l is the gauge-length and λ the elongation—

$$\frac{\text{contraction of area}}{\text{initial area}} = \frac{\omega}{\Omega} = \frac{\lambda}{l+\lambda}, = \frac{\lambda}{l} \text{ nearly.}$$

That is, the percentage of contraction is equal to the percentage of elongation, calculated in strictness on the stretched length of the bar. Hence, a definite relation between the elongation and contraction will only be found for the short length of the bar, which becomes almost perfectly plastic, and draws out during the last stage of the test.

The following numbers are from some measurements by the author in a gauge-length of 2 ins. including the fracture:

Material	Length in inches l	Contraction / Initial area $\frac{\omega}{\Omega}$	Elongation / Stretched length $\frac{\lambda}{l+\lambda}$
Iron bar	2	·24	·20
,,	2	·28	·20
,,	2	·42	·27
Angle iron	2	·15	·15
Iron plate	2	·12	·11
Steel plate	2	·39	·29
Delta metal	2	·09	·07
,, ,,	2	·27	·32

If there is this near agreement in the contraction and elongation in the short, plastically-yielding part of the bar near the fracture, then there can be no agreement in the contraction and the elongation in greater lengths of bar. The two measures of the ductility are only in agreement when the elongation is taken for a very short length of bar near the fracture.

65. *Elongation Equation.*—The total elongation of a bar in a gauge-length l is made up of two parts, one due to a general elongation, approximately uniform along the bar, and therefore proportional to l, the other due to a local stretch and contraction of section which occurs in the last stage of testing, after the maximum load has been reached. This local stretch depends on the sectional area of the bar, but not at all the length between gauge-points. Hence, at least very approximately, the total elongation e for bars of the same material and cross-section is—

$$e = a + bl \quad . \quad . \quad . \quad . \quad . \quad . \quad (1),$$

where a and b are constants. The first term on the right is the local, and the second term the general elongation. The equation is applicable if l is not less than the length affected by local stretching, or so great that the elongation is sensibly affected by the enlarged ends. The percentage of elongation is

$$e\% = 100\,\frac{e}{l} = 100\,\left(\frac{a}{l} + b\right),$$

or, if the numerical constant is included in the other constants,

$$e\% = \frac{a}{l} + b \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

It is clear that the percentage of elongation for a bar of a given size diminishes as the gauge-length is greater. This is well known ; and it is common to specify the gauge-length in which the elongation is measured. It is not so generally recognised that the part of the elongation due to local contraction depends on the section of the test bar, and that, therefore, the percentage of elongation in a given gauge-length increases as the section of the bar is greater.

In Germany, where much of the testing is done in State laboratories, the importance of Barba's law has been better recognised than elsewhere. A normal form of test bar has

been generally adopted, for both cylindrical and plate test-bars, with a gauge-length of 20 cms. (8 ins.) and a section of 3·14 sq. cms. (0·487 sq. in.). Such bars satisfy the relation,

$$l = 11{\cdot}3\sqrt{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3),$$

where l is the gauge-length and A the area of section. If bars of a different section must be used, the gauge-length is modified so that (3) is still satisfied. Such bars are termed proportional bars, and may be regarded as virtually similar bars.

Law of Variation of Percentage of Elongation in Geometrically Dissimilar Bars.—The law of variation of elongation with gauge-length is given in equation (2) ; it remains to find the variation when the cross-section varies. But the percentage of general elongation is independent of the size of the test bar, and only the variation of local elongation requires to be examined, that is, the term a in equation (2). Now, if the parts of two bars of similar cross-section affected by local contraction are similar after fracture, the extension due to local contraction must be proportional to the linear dimensions of the cross-sections. Or, since the exact form of the cross-section does not appear to much affect the elongation—

$$a = c\sqrt{A},$$

Putting this in equation (2), the percentage of elongation for any bars similar or dissimilar is given by the equation—

$$e\,\%_{\circ} = \frac{c\sqrt{A}}{l} + b \quad . \quad . \quad . \quad . \quad . \quad (4),$$

where c and b are constants for a given material. The first term on the right is the percentage of local, and the second term the percentage of general elongation. The equation applies if the gauge-points are not very close to the enlarged ends, and if l is not so short that the gauge-points fall within the local contraction. So far as the author has examined, l must not be less than from $2\sqrt{A}$ to $3\sqrt{A}$ in mild steel. No doubt this length depends somewhat on the quality of the material. The equation is a linear one, so that if values of $\sqrt{A}/l$ are taken as abscissæ and values of $e\,\%_{\circ}$ as ordinates the equation gives a straight line.

Fig. 52 shows observed values for a bar of mild steel plotted in this way. The points lie closely along a straight line except for very large values of $\sqrt{A}/l$. The equation cannot be expected to be quite exact, partly because small local variations of homogeneity modify the local contraction, and because for a similar reason the general elongation is never quite uniform along the bar. Nevertheless it will be found to express with practical accuracy the relation of elongation to gauge-length in bars of very different proportions, and, with suitable modifications of the constants, in bars of very different quality. It should be noticed that equation (4) satisfies Barba's law that the percentage of elongation is constant in similar bars of a given material.

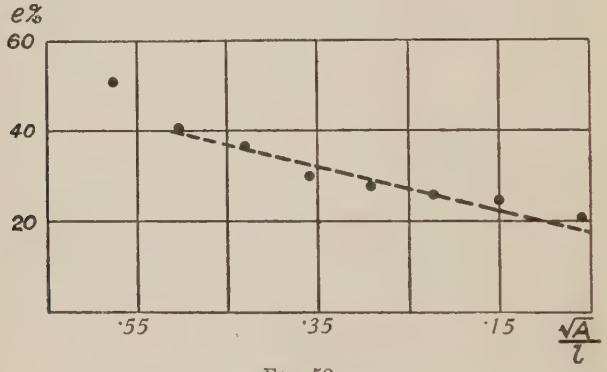


Fig. 52.

The following tables give the results of some of M. Barba's tests, with the constants deduced from them, and a comparison of the observed and calculated values of the elongation:

Annealed Soft Steel (Cylindrical Bars)

Diameter Varied

$$e\,\% = \frac{94\,\sqrt{A}}{l} + 21{\cdot}1 = \frac{83{\cdot}3d}{l} + 21{\cdot}1$$

Diameter d	Gauge-length l	$\frac{l}{d}$	e % Observed	e % Calculated	Error of equation
Inch.	Inches.		Per cent.	Per cent.	
0·8	4	5	37·5	37·8	+ 0·3
0·4	4	10	30·2	29·4	− 0·8
0·2	4	20	25·0	25·3	+ 0·3

HALF HARD STEEL (CYLINDRICAL BARS)

Diameter Varied

$$e\,\% = \frac{66{\cdot}9\ \sqrt{A}}{l} + 14{\cdot}4 = \frac{59{\cdot}3d}{l} + 14{\cdot}4$$

Diameter d	Gauge-length l	$\frac{l}{d}$	e % Observed	e % Calculated	Error of equation
Inch.	Inches		Per cent.	Per cent.	
0·8	4	5	25·9	26·3	+ 0·4
0·4	4	10	21·0	20·3	− 0·7
0·2	4	20	17·0	17·4	+ 0·4

These tables show that the equation is approximately true for a large variation of section (16 to 1) and constant gauge-length.

CYLINDRICAL TEST PIECES CUT FROM A SOFT STEEL BAR

Gauge-length Varied

$$e\,\% = \frac{60{\cdot}9\ \sqrt{A}}{l} + 22{\cdot}8 = \frac{54\,d}{l} + 22{\cdot}8$$

Diameter d	Gauge-length l	$\frac{l}{d}$	e % Observed	e % Calculated	Error of equation
Inch.	Inches.		Per cent.	Per cent.	
0·688	2	2·91	42·0	41·1	− 0·6
0·688	4	5·81	32·0	32·1	+ 0·1
0·688	6	8·73	29·3	29·0	− 0·3
0·688	8	11·60	27·2	27·5	+ 0·3
0·688	10	14·49	26·6	26·5	− 0·1
0·688	12	17·39	26·0	25·9	− 0·1
0·688	14	20·33	25·1	25·5	+ 0·3
0·688	16	23·31	25·0	25·1	+ 0·1
0·688	18	26·18	24·9	24·9	0·0
0·688	20	29·07	24·8	24·7	− 0·1

This verifies the equation for bars of constant section and widely different gauge-length (10 to 1).

TEST BARS OF STEEL PLATE

Rectangular Sections of Different Proportions

$$e\,\% = \frac{67{\cdot}6\ \sqrt{A}}{l} + 24{\cdot}1$$

Width	Thick-ness	Area	Gauge-length	$\frac{l}{\sqrt{A}}$	e % Observed	e % Calculated	Error of equation
Inches	Inch	Sq. inch.	Inches		Per cent.	Per cent.	
0·4	0·4	0·16	4	10·0	31·0	30·9	− 0·1
0·8	0·4	0·32	4	7·0	34·0	33·7	− 0·3
1·2	0·4	0·48	4	5·8	35·0	35·8	+ 0·8
1·6	0·4	0·64	4	5·0	37·2	37·6	+ 0·4
2·0	0·4	0·80	4	4·5	39·0	39·2	+ 0·2
2·4	0·4	0·96	4	4·1	40·8	40·7	− 0·1

52 33

This verifies the equation for test bars varying in area and in form of cross-section.

66. *Values of the Constants in the Elongation Equation for Different Materials.*—The author made a long series of tests for the British Standards Committee on mild steel ship and boiler-plates. In these tests the bars were marked in half-inch lengths, so that the percentage of elongation could be found for fracture at the centre of the gauge-length. From these results values of the constants in the elongation equation—

$$e\,\% = \frac{c\sqrt{A}}{l} + b \quad . \quad . \quad . \quad . \quad . \quad . \quad (5),$$

have been calculated and are given in the following table. Generally the constants b and c decrease as the thickness of the plates increases, showing that thick plates are less ductile. This might be expected as they are less worked in rolling. The $\frac{1}{4}$-inch plates, however, give low values, due probably to their temperature in rolling being too low.

VALUES OF CONSTANTS IN ELONGATION EQUATION

	Thickness of plate	Values of c	Mean values of c lengthways	Values of b	Mean values of b lengthways
		Ship-plates.			
	Inch.				
Motherwell . . . L.	$\frac{1}{4}$	85·2	77·4	16·2	16·7
Park Gate . . . L.		69·6		17·1	
„ . . . A.		77·9		13·4	
Motherwell . . . L.	$\frac{3}{8}$	83·3	85·2	21·0	19·2
Park Gate . . . L.		87·1		17·4	
„ . . . A.		75·0		17·5	
Motherwell . . . L.	$\frac{5}{8}$	52·5	58·6	22·1	20·1
Park Gate . . . L.		64·7		18·0	
„ . . . A.		55·4		17·5	
Motherwell . . . L.	$\frac{7}{8}$	65·6	59·9	19·1	17·3
Park Gate . . . L.		54·2		15·5	
„ . . . A.		48·3		15·5	
Motherwell . . . L.	$1\frac{1}{4}$	52·0	53·3	13·6	14·7
Park Gate . . . L.		54·5		15·7	
„ . . . A.		54·4		17·3	
Mean of all, lengthways	—	—	66·9	—	17·6
„ „ crossways .	—	—	65·6	—	16·2

VALUES OF CONSTANTS IN ELONGATION EQUATION—*continued*

——	Thickness of plate	Values of c	Mean values of c lengthways	Values of b	Mean values of b lengthways
	Inch.				
Boiler-plates.					
Motherwell . . . L.	$\frac{1}{4}$	105·4	94·5	19·7	17·7
Park Gate . . . L.		83·6		15·6	
„ . . . A.		59·3		11·3	
Motherwell . . . L.	$\frac{3}{8}$	86·3	81·3	21·2	20·0
Park Gate . . . L.		76·3		18·8	
„ . . . A.		62·0		19·9	
Motherwell . . . L.	$\frac{5}{8}$	77·4	72·6	19·2	19·4
Park Gate . . . L.		67·9		19·5	
„ . . . A.		69·6		19·0	
Motherwell . . . L.	$\frac{7}{8}$	74·2	70·6	19·0	18·9
Park Gate . . . L.		67·0		18·7	
„ . . . A.		71·5		15·8	
Motherwell . . . L.	$1\frac{1}{4}$	72·3	68·5	17·1	18·6
Park Gate . . . L.		64·7		20·1	
„ . . . A.		19·6		12·7	
Mean of all, lengthways	—	—	77·5	—	18·9
„ „ crossways .	—	—	56·4	—	15·7

Tests were also made on some steel plates containing different percentages of carbon, and these were tested both as received and after annealing. The following table gives the results :

VALUES OF CONSTANTS IN ELONGATION EQUATION

Unannealed Plates

Carbon	Thickness of plate	Constant c		Constant b	
	Inch.				
Per cent.	$\frac{1}{4}$	96·4	Means.	9·2	Means.
0·32	$\frac{1}{2}$	69·3	76·6	14·3	12·3
	$\frac{3}{4}$	64·0		13·5	
	$\frac{1}{4}$	70·4		10·3	
0·48	$\frac{1}{2}$	67·9	69·9	8·5	9·0
	$\frac{3}{4}$	71·5		8·1	
0·60	$\frac{1}{4}$	64·5	64·5	8·3	8·3

VALUE OF CONSTANTS IN ELONGATION EQUATION—*continued*

Annealed Plates

Carbon	Thickness of plate	Constant c		Constant b	
	Inch.				
Per cent.	$\frac{1}{4}$	82·1	Means.	16·5	Means.
0·32	$\frac{1}{2}$	67·5	72·2	14·7	14·7
	$\frac{3}{4}$	67·0		12·8	
	$\frac{1}{4}$	50·8		15·2	
0·48	$\frac{1}{2}$	62·2	60·4	14·2	13·9
	$\frac{3}{4}$	68·3		12·2	
	$\frac{1}{4}$	69·4		10·8	
0·60	$\frac{1}{2}$	51·0	60·1	12·0	11·0
	$\frac{3}{4}$	59·9		10·3	

The constant c which depends on the local extension varies somewhat irregularly, on the whole decreasing as the percentage of carbon increases, but not differing much on the average in the annealed and unannealed bars. The constant b, which is the percentage of general elongation, varies more regularly, decreasing as the percentage of carbon increases, and being markedly greater in the annealed than in the unannealed bars. This certainly suggests that the percentage of general extension is a better index of the quality of the material than the percentage of total extension.

In the case of forgings, and especially in the case of tyres and axles, it is necessary to use very small test bars with a gauge-length of 2 or 3 inches. The results of tests on axle steel and the harder steel used for tyres is given in the following tables. Half the bars were of 0·5 sq. in. and half of 0·25 sq. in. section. The tenacity of the axle steel was 32 to 36 tons per sq. in., and that of the tyre steel 48 to 52 tons per sq. in.

VALUES OF CONSTANTS FOR MR. FAIRHOLME'S TESTS

Axle Steel

Mark	c		b	
A_1	42		21·5	
A_2	50		21·1	
B_1	39	Mean	18·1	Mean
B_2	42	39·2	19·3	20·6
C_1	31		22·0	
C_2	31		21·5	

Tyre Steel

Mark	c	b
A_2	34	15·0
B_1	21	11·8
B_2	25 Mean 27·2	12·6 Mean 13·1
C_1	24	14·0
C_2	32	12·0

The following constants for some other metals are interesting:

Gun-metal (cast) . . . $e\% = \frac{8{\cdot}3\sqrt{A}}{l} + 10{\cdot}6$

Rolled brass . . . . $e\% = \frac{101{\cdot}6\sqrt{A}}{l} + 9{\cdot}7$

Rolled copper . . . $e\% = \frac{84\sqrt{A}}{l} + 0{\cdot}8$

Annealed copper . . . $e\% = \frac{125\sqrt{A}}{l} + 35$

The difference between the constants for the hard rolled copper bar and a similar bar annealed is interesting.

67. *Quality Factor.*—Tension tests furnish as a means of estimating the quality of material—(1) the breaking stress p or maximum load divided by the initial cross-section; (2) the percentage of elongation in a given gauge-length; and (3) the contraction of area at fracture expressed as a percentage of the initial area. Two of these qualities are usually selected as characterising the essential qualities of strength and ductility. But then a difficulty arises as there are two criteria to consider, and attempts have been made to combine the two quantities so as to obtain a single quality figure. Wöhler suggested that the sum of the breaking stress and contraction of area should be taken as the quality factor; Tetmajer proposed the product of the breaking stress and percentage of elongation—a quantity roughly proportional to the work expended in breaking per cubic unit; and other suggestions have been made, shown in the following statement:

	Quality factor.
Wöhler	$p + c$
Modified Wöhler	$p + e$
Tetmajer	$p\,e$
Dormus	$p^2\,e$

All these factors must be regarded as rather empirical indices of quality which can only be used safely for materials of the same kind and for a limited range of quality. A 30-ton steel with 24 per cent. elongation, the modified Wöhler factor for which is 54, is for many purposes an excellent material. A 44-ton steel with 16 per cent. elongation would have the same quality factor, but for such purposes would be unsuitable.

Of these factors the only one much used in this country is the quality factor $q = p + e$, and if limits of strength are specified, it has a use in fixing the minimum elongations of steels of somewhat different strength. Thus steels of 28 tons strength and 26 per cent. elongation, and 30 tons strength and 24 per cent. elongation, and 32 tons strength and 22 per cent. elongation, have the same quality factor and are probably of equal constructive value. But if any such quality factor is to be used it must be remembered that the elongation must be determined on test bars either of the same dimensions or geometrically similar. The following table gives the quality factor $q = p + e$ for bars of various quality, and for different cross-sections and a fixed gauge length:

QUALITY FACTOR. PLATES WITH VARYING PERCENTAGE OF CARBON

(Gauge-length, 8 inches)

Annealed Plates

Carbon	Thickness of plate.	Breaking stress. tons per sq. in.	Quality factor when area of section:			
			0·5 sq. in.	1·0 sq. in.	1·5 sq. in.	2·0 sq. in.
Per cent.	Inch.	Tons				
0·32	½	29·9	52·7	50·7	50·4	49·9
	¾	30·4	51·4	50·6	50·3	47·9
	1	30·7	49·4	47·9	46·7	44·8
	1½	34·0	56·7	54·4	50·4	48·1
0·48	½	38·4	59·7	55·5	52·5	50·1
	¾	39·0	58·1	55·3	52·6	49·7
	1	39·0	57·1	53·9	51·6	47·2
	1½	40·5	57·5	60·4	60·2	59·5
0·6	½	48·8	56·4	47·2	45·3	39·8
	¾	48·6	52·6	50·8	47·0	45·8

The quality factor has been chiefly used in this country in specifications for forgings, in which case small test bars

are used. The following table gives mean results of tests of tyres and axles, and shows the variation of quality factor for the same material when the test bars are of different sizes:

QUALITY FACTOR. TYRES AND AXLES

		QUALITY FACTOR		
Gauge length		2 ins.	2 ins.	9 ins.
Area of section		0·25 in.	0·1 in.	0·9 in.
Material	Breaking stress in tons per sq. in.			
Tyres	34·6	64·9	69·0	64·4
Axles	49·8	69·7	72·5	69·4

CHAPTER V

BEHAVIOUR OF MATERIALS UNDER TEST

[illegible] *Influence of Form of Test Bar. Suppression of Drawing Out.*—The elongation in ordinary test bars is measured on a portion of uniform section, and the measurements are not extended quite up to the enlarged ends by

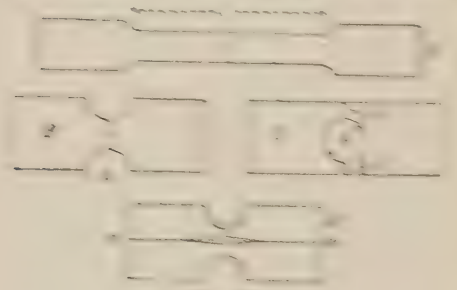


Fig. [illegible]

which the specimen is held. The enlarged ends diminish the drawing out of the parts nearest them, and if the part between the enlarged ends is very short, the drawing out, contraction, and strength are all affected.

A plate perforated with a row of holes, or formed like a or b (fig. [illegible]), is virtually a very short test bar. In reporting on riveted joints for the Institute of Mechanical Engineers,[1] the author noticed that in some cases the breaking stress of a perforated plate was greater than that of a plain test bar of the same material. Shortly after, this was shown more distinctly in some experiments of the Board of Trade on riveted joints,[2] and in experiments by Professor Kennedy for the Institute of Mechanical Engineers. In these last experiments, perforated steel plates ½ inch thick were 10·7 per cent. and ⅝-inch plates 17·8 per cent. stronger per sq. in. than plain test bars of the same material.[3]

[1] *Proc. Inst. of Mech. Engineers*, 1881, p. 319.
[2] *Experiments on Steel. Memorandum of the Board of Trade*, 1881, p. 18.
[3] *Proc. Inst. of Mech. Engineers*, 1881, p. [illegible].

It will be seen that the punched plates lose from [illegible] per cent. of strength in ½-inch plates to [illegible] per cent. in 1-inch plates. But in all other cases there is a gain of strength in the perforated plates. This amounts to about [illegible] per cent. in the ½-inch plates, [illegible] per cent. in the ¾-inch plates, [illegible] per cent. in the ½-inch plates, and [illegible] per cent. in the 1-inch plates. That this is due to the dimension of contraction the following table shows. In punched plates the contraction is diminished, but the metal is also injured by the process of punching.

	[illegible]			
	[illegible]	[illegible]	[illegible]	[illegible]
Unperforated	[illegible]	[illegible]	[illegible]	[illegible]
Punched	[illegible]	[illegible]	[illegible]	[illegible]
Punched and annealed	[illegible]	[illegible]	[illegible]	[illegible]
Punched and bored	[illegible]	[illegible]	[illegible]	[illegible]
Drilled	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

	[illegible]			
	[illegible]	[illegible]	[illegible]	[illegible]
Unperforated	[illegible]	[illegible]	[illegible]	[illegible]
Punched	[illegible]	[illegible]	[illegible]	[illegible]
Punched and annealed	[illegible]	[illegible]	[illegible]	[illegible]
Punched and bored to [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Drilled	[illegible]	[illegible]	[illegible]	[illegible]

Some experiments by Mr. [illegible][1] [illegible] very clearly the dependence of the breaking stress, estimated in the usual way by dividing the breaking load by the bottom section, on the amount of drawing out before fracture.

The test bars of the forms shown in fig. [illegible] were all cut from the same plate, and the holes were in all cases [illegible] ton. [illegible] inch) diameter. The width [illegible] varied in different test bars.

[1] [illegible]

Form	Dimensions		Ratio $\frac{b}{d}$	Elongations per cent			Breaking stress, kilos per sq. mm.	
	Width b mm.	Thickness t mm.		Of hole	In 50 mm.	In 200 mm.		
A	35	12	—	—	—	25½	44·0	
B	46·8	12	1·94	50	26	—	47·4	
	31·8	12	1·32	40	18	—	48·0	Mean
	18·0	12	0·75	27½	14	—	47·7	47·8
	12·5	12	0·52	21	12	—	48·0	
C	54·0	12	2·25	54	28	—	46·6	
	44·0	12	1·83	50	26	—	47·0	
	34·0	12	1·42	46	22	—	45·8	
	28·4	12	1·18	41½	22	—	45·0	Mean
	23·3	12	0·97	37½	20	—	48·8	45·7
	18·6	12	0·77	33½	16	—	45·2	
	13·0	12	0·54	25	14	—	45·5	
	7·6	12	0·32	21	10	—	45·1	

It will be seen that form B is 9 per cent. and form C is 4 per cent. stronger than the simple test bar A. This is the effect due to diminution of the contraction of area by the neighbourhood to the breaking section of less strained material. Now as the breadths at corresponding points of B and C are equal, it looks at first sight as if B and C ought to behave alike, whereas, apparently, in the experiments B is stronger than C. It will be seen, however, that the material near the point of fracture is not in identical conditions in the cases B and C. Suppose two bars of the form D are placed back to back and broken. The material at the place of fracture is now identically in the same state as in form C, and contraction takes place not only round the semicircular holes, but along the edges *m m*. Weld together the pieces along this line, and the contraction along *m m* can no longer occur. The piece is then identical with form B; it has less contraction than C, and ought to be stronger. The experiments show that it is so.

Mr. Richards made some interesting experiments at the Barrow Company's Steel Works on test bars similar to Mr. Strohmeyer's bars A and B. The material was mild steel plate ½-inch thick made by the Siemens process. Two pieces had parallel sides like ordinary test bars. The other specimens were indented on each side by a semicircular drilled hole, leaving a section between of varying width. The results are given in the following table:

Form.	Width b inches.	Thickness. t	Contraction of area per cent.	Contraction of width per cent.	Contraction of thickness per cent.	Breaking stress in tons per sq. in.
A	1	·495	52·5	27·0	33·3	32·01
	1	·490	53·5	27·5	35·9	32·47
B	·645	·495	45	19	32	36·64
	·650	·500	46	19	33	36·52
	·995	·502	47	11	37	36·82
	·995	·495	42	12	34	37·05
	1·47	·502	31	8	26	36·18
	1·46	·500	36	10	30	35·88
	2·28	·495	42	9	36	35·72
	2·27	·495	43	8	37	35·72

Here the plates of form B, equivalent to perforated plates, are on the average 12·6 per cent. stronger than the parallel-sided bars of form A, and the strength is very uniform, considering the different widths of the specimens. The contraction of area in form A is 53 per cent., while in form B it is only 41 per cent., so that there is a diminished contraction to account for the increase of strength. Further, while the contraction of thickness is nearly the same in form A and form B, the contraction of width, which is what would be affected by the form of the specimen, is 27·2 per cent. in form A, and only 11·9 per cent. in form B.

69. *Strength of Screw Bolts.*—The shortest possible bar is formed by turning a groove with a very slightly rounded bottom. The following experiment, on two bolts of Whitworth compressed steel, gives the strength of a bar of extremely tough material thus shaped. The heads and nuts of the bolts were turned to fit spherical seatings, so that the stress was quite fairly applied. A groove, a little rounded at bottom, like a Whitworth screw thread, was turned in the body of one bolt as at A (fig. 54), and the other was turned in the form shown at B.

	Diameter.	Breaking load, in tons.	Breaking stress, in tons per sq. in.
Form A	1·560	101·77	53·25
Form B	1·487	62·35	35·87

B elongated 60 per cent. in 2 ins., and the contraction of area was 54·6 per cent. For A the elongation and contraction were practically *nil*.

Professor Martens[1] has carried out tests of the strength

[1] *Zeitsch. d. Ver. Deuts. Eng.*, 1895.

of bars on which screw threads of different forms had been chased. Four forms were tried: (1) a V-thread with sharp angles; (2) a Whitworth thread similar to the last, but with the usual rounding at top and bottom of thread; (3) a Sellers thread; and (4) the very similar thread of the Union of German Engineers. For bolts 1 inch in diameter, bars originally 1·4 inch in diameter were used, of a tensile strength in ordinary test bars of 23·9 tons per square inch; for bolts $\frac{1}{2}$ inch in diameter, bars of the same size originally, but of a tensile strength of 27·7 tons per square inch. There was no marked difference in the ultimate strength with different forms of thread, but the sharp-angled V-thread was slightly the strongest. The strength per square inch of section (taken at the bottom of the thread) was about 14 per cent. greater than the strength of plain bars without screw threads. In some cases the tension was applied to the nut of the bolt, and the nut was kept turning while the bar was being tested. The effect of this is to introduce torsional stress additional to the tension. In this case the strength was about 15 to 20 per cent. less than that of plain bars, so that the torsion reduced the load the bolt would carry about 30 per cent.

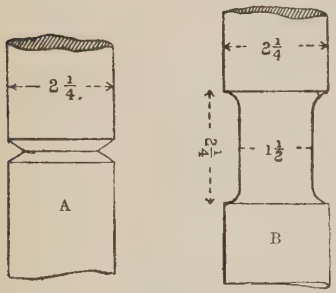


FIG. 54.

In some recent tests of Whitworth & Sellers threads by Mr. Matthews at the works of Messrs. Armstrong, Whitworth & Co. a weight of 400 lbs. was allowed to fall a distance of 3 to 12 inches and expend its energy in stretching a bolt. When the bolts were of very mild steel the Whitworth and Sellers screws sustained nearly the same number of blows before breaking, the Whitworth thread having a slight advantage. But with 40- to 50-ton steel, such as is now used in high class construction, the Whitworth screw sustained a greater number of blows than the Sellers.

70. *Abrupt Change of Section: Nicked Specimens.*—At any abrupt change of section the stress on cross-sections cannot be uniform. The less strained metal hinders the extension of other metal near it. If the material were perfectly elastic the stress at any re-entrant angle would be infinite, but the

plasticity of all ordinary materials diminishes very greatly the inequality to stress. Nevertheless the inequality exists, and it counteracts the gain of strength due to suppression of drawing out.

Two pieces of the same cast iron were tested, one in the form of an ordinary test bar, the other with a square collar in the middle of its length. The re-entrant angles at the collar were virtually nicks. The breaking weights were—

Plain bar	13·875 tons per sq. in.
Collar bar	11·980 „ „

showing a loss of 13·6 per cent. of strength, due to the inequality of distribution of stress caused by the collar.

Sir B. Baker made some interesting experiments on steel plates with artificially produced cracks.[1] A fine saw-cut was

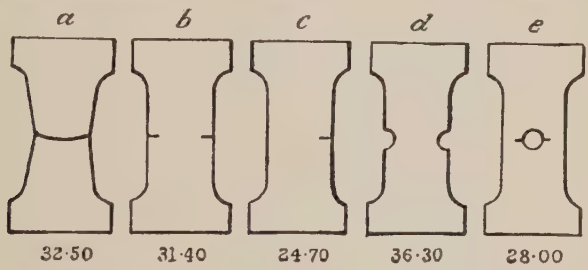


Fig. 55.

made at one or both edges of the specimen, and then, raising the specimen nearly to welding heat, the saw-cut was closed up so far as to be rendered invisible. Fig. 55 shows a set of specimens of the same steel. Specimen *a* was an ordinary test bar; *d* was a bar with semicircular notches, so that it was virtually a short bar; *b* was a bar with a saw-cut or crack on both sides; *c* a bar with a saw-cut or crack on one side; *e* a perforated bar with a crack on each side of the hole.

The breaking stress in tons per sq. in. is given under the figures. It will be seen that the short bar *d* is stronger than the plain test bar *a* by 12 per cent.; but the nicked bar *b* is weaker by 3½ per cent. Considered as a short bar, *b* should have carried as much as *d*; the inequality of distribution of stress has therefore reduced its strength by 15½ per cent. Similarly *e* is weaker than *d* by 22 per cent. It is clear, therefore, that, in the case of nicked bars, the increase of

[1] *Minutes of Proc. of Inst. of Civil Eng.*, vol. lxxxiv. p. 165.

strength which would result from the virtual shortness of the bar is more than counteracted by the inequality of stress on the section of fracture. Sir B. Baker found with specimens of india-rubber a loss of strength in nicked specimens of 60 or 70 per cent., and that is probably due to the fact that india-rubber, although it deforms enormously, is really less plastic than steel, and consequently the variation of stress is greater.

71. *Influence of Time on the Ultimate Elongation.*—Some experiments of Colonel Maitland at Woolwich[1] show that, contrary to a common prejudice, the ultimate elongation is increased by very rapid loading. Colonel Maitland experimented on a steel which, in unhardened specimens of 2 inches in length between shoulders, broke in the testing-machine at 26 tons per sq. in. and with 27 per cent. of elongation. A specimen was then screwed into blocks arranged so as to fall vertically in a slide. After a certain height of fall the top block was arrested by stops and the specimen broken by the momentum of the lower block. Broken in this sudden way the ultimate elongation was 47 per cent. Specimens were then screwed into plugs fitting a strong tube, and broken by exploding gunpowder and guncotton between the plugs. The plugs were driven out in opposite directions, breaking the specimen connecting them. Under these circumstances the ultimate elongation was from 47 to 62 per cent. The explanation of these results appears to be that with very rapid increase of stress there is not time for the formation of a short local contraction, but the general extension continues up to the breaking point.

On the other hand, however, M. Lebasteur (*Ann. des Ponts et Chaussées,* 1890) found that the elongations of steel bars fractured by high drop impact tests are nearly identical with the elongations of similar bars under slow tension. The appearance of the fracture is the same in the two cases.

72. *Elastic Afterworking.*—In iron and steel the time increase of extension, and the lag, when the load is removed, is not very large, but in some other materials these are more marked. Fig. 56 is the stress-strain diagram for a bar of magnesium, from measurements made by Martens. This metal has no P-point. If at a point A the load is kept constant the elongation increases, but at a diminishing rate.

[1] 'The Treatment of Gun Steel.' *Proc. Inst. of Civil Engineers,* vol. lxxxix. p. 120.

Similarly at B, C, the effect of pauses in loading is shown. For a given duration of pause the increment of extension is greater the greater the stress. It is more for five minutes' pause at B than at A, and at C than at B. At C the load was nearly all taken off, and at D is shown the gradual decrease of elongation after unloading during a pause of five minutes. Similarly at H is the decrease during another pause for five minutes.

73. *Hardening Effect of Long-continued Stress.*—Experiments on the influence of time on the extension and breaking stress of wires have been made by Mr. J. T. Bottomley in Lord Kelvin's laboratory.[1] Eight specimens of soft iron wire were tested by gradually increasing stress, applied in ten minutes of time in each case. They broke with 43½ to 46 lbs. (mean 45·2 lbs.), with elongations varying from 17 to 22 per cent. Another specimen, left with 43 lbs. hanging on it for 24 hours and then broken by gradual increase of stress during 25 minutes, broke with 49¼ lbs., with 15 per cent. elongation. Another, left for 3½ days with 43 lbs. hanging on it, and then broken by increasing stress, bore 51½ lbs. and elongated 14·4 per cent. A bar, loaded first with 40 lbs. and broken by gradual addition of load during two months, broke with 57¼ lbs. The slower loading had therefore increased the strength by nearly 27 per cent. The increase of breaking stress and diminution of elongation are commonly attributed to a hardening effect of long-continued stress. But the result seems complicated by the influence of time on the local drawing out in the neighbourhood of the fracture. Generally, the more slowly the load is applied the shorter is the local contraction and the less the contraction of area.

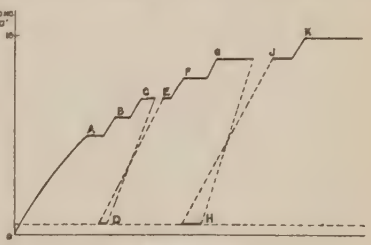


FIG. 56.

74. *Influence of Time in Testing.*—Some tests on iron and mild steel given in the Report of the French Commission (Commission des Méthodes d'Essai des Materiaux, i. p. 344) show that for tests carried out in periods varying from a few seconds to ten minutes or more, there is very little difference in the breaking stress or percentage of ultimate elongation.

[1] Article 'Elasticity,' in the *Encyclopædia Britannica*.

Prof. Bauschinger carried out a very careful series of experiments on the influence of different rates of loading in testing.[1] The effect of time is shown in an increase of deformation while the load remains constant. In materials having an elastic limit this occurs only after the elastic limit is passed. In materials with no elastic limit it is observable from the first. In certain cases the maximum load attainable is less when the extension is slow than when it is rapid. Bauschinger's latest experiments were on test pieces of rectangular section generally about $1\frac{1}{2}$ inch wide and 8 inches effective length. The general results for different materials may be summarised as follows: (*a*) For steel, the duration of the tests after the elastic limit was reached being 26, 41, 46, and 77 minutes, the influence of speed of loading, though recognisable in the stress-strain diagrams, is so slight as to be easily masked by the ordinary differences of quality of the material. (*b*) For wrought iron, normal or annealed, the speed of loading does not appreciably affect the results. (*c*) For copper, no distinct elastic limit or yield point was observable. The results as to speed of loading were the same as for steel and wrought iron. (*d*) For zinc, there was no elastic limit or yield point, and the maximum load was greatest for the bars tested most slowly. But Bauschinger thinks this was due to differences of quality in the material. (*e*) For lead, the influence of speed of loading on the maximum stress was also unmistakable, but its influence on the elongations is hardly to be traced. (*f*) For tin, a limit of elasticity was found at 0·136 ton per sq. in. The influence of speed on the elongation is very marked, the elongation increasing as the duration of the test increased. (*g*) For bronze (cast), a true limit of elasticity could scarcely be found, but there was a practical limit at 3·9 tons per sq. in., and a yield point at 6·35 tons per sq. in. The influence of speed was almost completely masked by differences in the quality of different test bars. The same result was found with brass. (*h*) For cast iron, the influence of speed of loading was practically negligible. Bauschinger points out that with materials which continue stretching while the load is constant, or, as he says, exhibit *afterstretch*, the stress-strain diagram when the load is again increased rises steeply, so that the diagram at slow speed overtakes that taken at fast speed.

75. *Measure of the Toughness of a Material.*—A material

[1] *Mitth. aus dem mech. techn. Laboratorium der k. techn. Hochshule zu Munchen*, Part xx., 1891. *Proc. Inst. Civil Engineers*, cvii. p. 434.

is said to be tough if for great straining action it suffers large deformation. It is brittle if it breaks with little deformation.[1]

Ordinarily with iron and steel it is common to take the percentage of ultimate extension or percentage of contraction of area as a measure of the toughness. Martens has shown that the ratio of the yielding strength to the breaking strength p_s/p_B measures the degree of mechanical working to which a metal has been subjected. For instance, for annealed mild steel this ratio is 0·55 to 0·75. For the same material cold drawn it may be 0·95. This suggested that the ratio p_B/p_s might be taken as a measure of toughness. Following a research of Reiser, Martens takes finally for the measure of toughness—

$$\zeta = \frac{p_B}{p_s} \cdot \lambda,$$

where λ is the ultimate elongation per unit length, and he finds that this measure for very different materials accords with experience. The following are some values given by Martens:

Material	Strength, tons per sq. in.		$\frac{p_s}{p_B}$	$\frac{p_B}{p_s}$	100 λ elongation per cent.	$\frac{p_B}{ps}\lambda$
	Yield. p_s	Breaking p_B				
Wire (from Fischer):						
Steel . .	38·5	51·7	0·74	1·3	2·5	0·03
Lead . .	0·39	0·69	0·57	1·7	8·7	0·15
Iron . . .	11·1	19·3	0·58	1·7	14·0	0·24
Copper . .	2·97	15·7	0·19	5·3	31·0	1·64
Forged Iron:						
Normal . .	14·5	22·8	0·64	1·58	27·9	0·45
Annealed . .	13·3	21·1	0·63	1·58	28·2	0·44
Hardened. .	20·0	30·8	0·65	1·54	13·5	0·21
Thomas steel:						
Normal . .	18·9	26·1	0·75	1·38	28·0	0·39
Annealed . .	15·7	24·2	0·65	1·55	29·6	0·46
Hardened. .	23·8	38·5	0·62	1·62	14·7	0·24
Martin steel:						
Normal . .	13·8	22·2	0·62	1·62	32·7	0·53
Annealed . .	11·2	20·1	0·56	1·80	37·4	0·67
Hardened. .	23·7	37·8	0·63	1·89	14·1	0·22
Martin steel:						
Normal . .	12·9	21·9	0·59	1·70	33·6	0·55
Annealed . .	11·8	20·2	0·58	1·71	32·8	0·58
Hardened. .	24·9	37·3	0·67	1·50	13·8	0·21
Gun steel . .	25·0	43·0	0·58	1·72	17·0	0·29
Rail steel . .	23·5	40·4	0·53	1·72	15·3	0·26

[1] In this paragraph the author follows generally Martens, *Materialienkunde*, i. p. 244.

The toughness is on this method determined by a tension test, and, strictly, by a tension test on a bar of normal proportions. It is to be taken as a practical, not an absolute measure.

76. *Change of Position of the Elastic Limit under Cyclical Variations of Stress. Recovery of Elasticity by Rest.*—Bauschinger[1] first observed accurately the fact that the elastic or proportional limits are not fixed stresses depending only on the material, but vary in position if the material is subjected to certain ranges of variation of stress repeated even a few times.

Treating tensions and extensions as positive and thrusts and compressions as negative, as in fig. 39, the following statement gives the general result of Bauschinger's investigations. By subjecting a bar to cyclical variations of stress over a definite range both limits of elasticity can be raised or both lowered, but not necessarily by equal amounts. The range of perfect elasticity decreases as the smaller of the limiting stresses increases. Further, there is now strong evidence that the elastic range established for cyclical variation of stress is the maximum range of stress to which a bar can be subjected, without ultimately breaking from fatigue when the repetition of straining is indefinitely repeated.

The elastic limit in tension, observed in a first loading of a material such as steel, is a limit artificially raised by processes of manufacture. A few reversals of tension and thrust through a range less than the primitive elastic range establishes a new and lowered tension limit. A range of stress between equal tension and thrust and less than the primitive elastic range can be found, through which, if the straining is repeated indefinitely, the material is perfectly elastic. The limiting stresses in this case are termed the *natural elastic limits*. Similar elastic limits can be established for unequal thrust and tension.

Some of Bauschinger's observations are plotted in fig. 57. Four stress-strain curves are shown for each of two series of tests, the scale of extensions being very large. The point at which yielding sensibly commenced is marked by a dot. The exact limit of proportionality for each loading is shown by a circle marked *e*.

[1] I. Bauschinger: *Dingler's Journal*, Bd. 224, s. 5; *Civilingenieur*, 1881, s. 290; *Mitth. aus dem Mechanisch-technischen Laboratorium in München*, Heft XIII. and XXV.

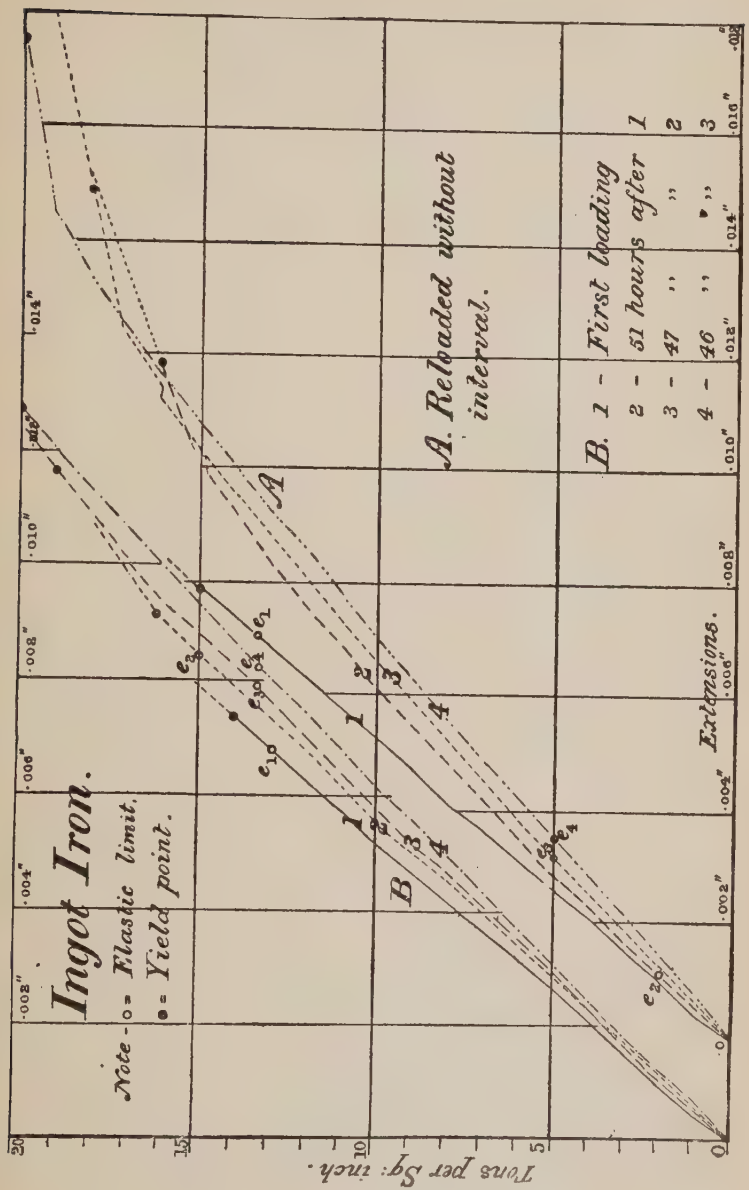

Ingot Iron.
Note - o = Elastic limit.
• = Yield point.
A. Reloaded without interval.
B. 1 - First loading
2 - 51 hours after 1
3 - 47 " " 2
4 - 46 " " 3
Extensions.
Tons per Sq. inch.
0
5
10
15
20
.002"
.004"
.006"
.008"
.010"
.012"
.014"

FIG. 57.

In the series of tests A the bar was reloaded without any sensible interval of time. The yield point rises at each loading, but the elastic limit falls in the second loading almost to zero. In series B an interval of about fifty hours was allowed between each loading. In this case the yield point rises as before, but the elastic limit rises also at each successive loading. Comparing the two series, it appears that the elastic or plastic recovery during the fifty-hour pause (unloaded) raised the elastic limit from the positions shown in A to those shown in B.

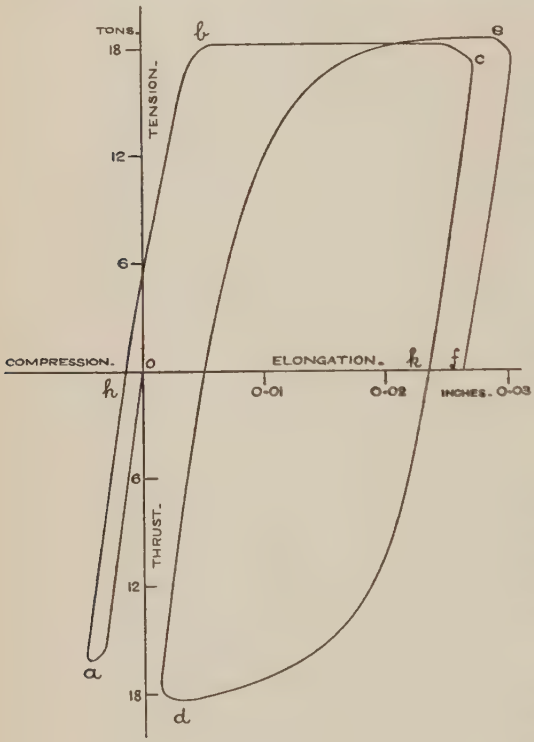


FIG. 58.

If a material is strained to or beyond the yield point, unloaded, and again immediately loaded—

(*a*) The breaking extension is diminished, and the breaking load somewhat increased.

(*b*) The elastic limit is lowered sometimes to zero, and the modulus of elasticity is a little diminished.

(*c*) The yield point is raised to the stress corresponding to the previous load.

If after the first loading a period of quiescence is allowed before the second loading:

(*a*) The elastic limit rises sometimes above its initial value.
(*b*) The yield point rises gradually above the stress corresponding to the previous load.

77. *Effect of Overstrain. Elastic Hysteresis.*—Mr. Thomas

Gray [1] made some interesting experiments on the imposition and removal of loads exceeding the elastic limit. Autographic diagrams were taken, in which the deformations were very greatly magnified.

Fig. 58 shows a test in alternate tension and compression of a bar of mild steel, $1\frac{1}{8}$ in. diameter and 3 ins. gauge-length. Thrust was first applied till a yield point was reached at *a*. The load was then gradually removed and a tension applied till a yield point was reached at *b c*. The

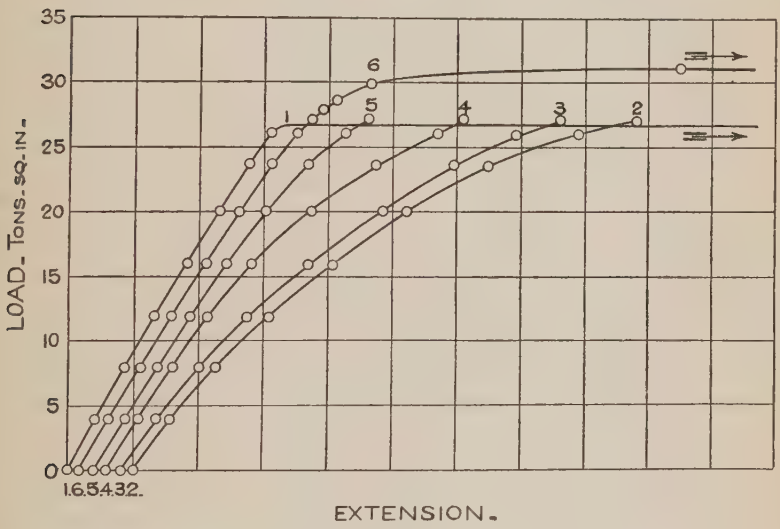


Fig. 59.

load was again removed and compression applied to *d*, and another cycle of variation of stress imposed ending at *f*. The first compression line *o a* is nearly straight, corresponding to a coefficient $E = 29{,}500{,}000$. But the material having been overstrained at *a* has become semi-plastic, and the return line *a b* is more or less curved throughout. This is still more the case with the line *d e* after the material had been overstrained both in tension and compression. Further, the stress-strain lines form loops, the area of which represents work expended in molecular friction, and which may be termed hysteresis loops.

[1] *Trans. Am. Soc. of Mech. Eng.*, 1897.

78. *Recovery of Metals from Overstrain.*—Mr. James Muir [1] has investigated the phenomenon of the recovery of metals from the semi-plastic condition, induced by straining beyond the elastic limit, by lapse of time, by heating, and by mechanical vibration. The first effect of overstrain is to

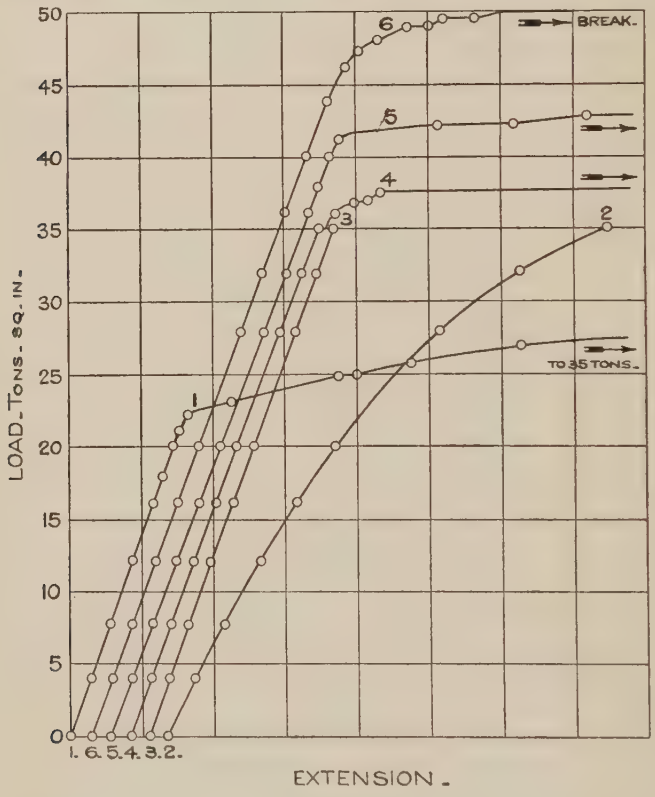


Fig. 60.

lower the elastic limit, it may be, to zero. Fig. 59 shows the gradual recovery of elasticity with lapse of time. It shows the extensions during a series of successive loadings. In loading 1, the yield point was reached at 27 tons per sq. in., and the bar took a large extension. Curve 2 shows the extensions in a test shortly after the first. It will be seen that this line is curved almost throughout. In plotting these

[1] *Phil. Trans.*, v. 193, p. 1, 1900. Also *Proc. Roy. Soc.*, vol. 67, p. 461, 1900.

curves, to save space they have been sheared back $\frac{1}{500}$th of an inch for each 4 tons of stress. Curves 3, 4, 5, and 6 were obtained at intervals of 4, 23, 70, and 147 hours. The curves are progressively less curved, showing a regular restoration of elasticity. In the sixth loading the bar was almost perfectly elastic up to the original yield point at 27 tons. When the loading was carried beyond this, a new but not very well-marked yield point was reached at a little over 30 tons per sq. in. After this the material was again

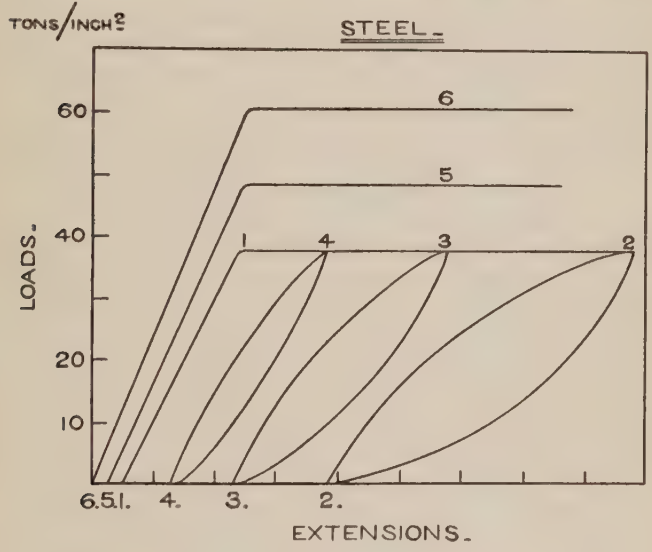


Fig. 61.

semi-plastic, and again gradually recovered elasticity in four days. The recovery of elasticity can be hastened remarkably by a very moderate heating. Three or four minutes at 100° C. were found to bring about a considerable restoration of elasticity.

Fig. 60 shows the tests of a specimen dipped in boiling water after overstraining. Curve 1 shows the stress-strain diagram for the first loading, the curve being sheared back as mentioned above. Curve 2 is the diagram after twenty minutes, and shows the loss of elasticity due to straining beyond the yield point. Curve 3 shows the diagram after immersion for four minutes in boiling water. Mr. Muir found

that mechanical vibration, instead of causing recovery from recent overstrain, made the material distinctly less elastic.

79. *Rise of Yield Point after Recovery from Overstrain.*—Mr. Muir found that if an overstrained steel bar was restored by moderate heating and then retested, it had a yield point higher than the primitive yield point. Thus in fig 61, 11 is the curve for first loading, showing a well-marked yield point at 38 tons per sq. in., elongating 0·13 in. in 4 ins. Curves 22, 33, 44, show the semi-plastic hysteresis loops obtained in loading and unloading after overstraining: 2 was taken shortly after 1; 3 after an interval of 1¾ days; and 4 after an interval of two weeks. The bar was then heated to 200° C., and curve 55 obtained showing complete restoration of elasticity and a new yield point at 49 tons per sq. in. Again heated to 200° C., after overstraining in the previous test curve 66 was obtained, showing again a restoration of elasticity and a new yield point at 60½ tons per sq. in.

80. *Effect of Repeated Annealing.*—If a bar of mild steel is heated up to an annealing temperature (about 750° C.) before testing, the yield point is either unaffected or is slightly lowered. If steel has been overstrained, is annealed, it is completely restored to the condition before overstraining. That is, annealing produces an effect different from moderate heating.

MILD STEEL BAR, No. 1432

Original diameter = 0·749 in.; area = 0·4406 sq. in.; clips 8 in. apart

No. of loading	Initial diameter at each loading	Initial area for each loading	Load put on, tons	Load put on, tons per sq. in. of original section	Load at yield point, tons	Stress at yield point, tons per sq. in. of		Elongation in original 8 in.	
						Original initial section	Reduced initial section for each loading	For each loading	Total from beginning of test
								in.	in.
1	0·749	0·4406	8·05	18·27	7·34	17·11	17·11	0·20	0·20
2	0·738	0·4278	8·30	18·84	7·25	16·45	16·95	0·24	0·44
3	0·727	0·4152	8·06	18·52	7·35	16·68	17·70	0·26	0·70
4	0·715	0·4015	8·06	18·29	7·15	16·23	17·81	0·29	0·99
5	0·702	0·3870	8·06	18·23	6·68	15·16	17·26	0·32	1·31
6	0·689	0·3728	8·01	18·18	6·88	15·61	17·78	0·39	1·70
7	0·677	0·3599	7·00	15·89	5·67	12·87	15·75	0·21	1·91
8	0·672	0·3547	8·68	19·70	5·79	13·14	16·32	1·85	3·76 broken

The table[1] above gives the results of some tests on a bar successively loaded to point a little beyond the yield point, and then annealed and the test repeated. Fig. 62 gives the autograph diagrams taken during each loading.

The yield point fell from 17·11 to 16·32 tons per sq. in. after eight loadings and annealings. The difference is not great. The total elongation of the bar was 3·76 ins. in 8 ins., or 47 per cent. in the aggregate during eight tests.

The final full curve is a diagram of a test to fracture after eight loadings and annealings, and when the section of the bar was sensibly less than at first.

The dotted curve is for a bar of the same steel broken in one test without annealing. The total elongation in that case was 28½ per cent. in 8 ins., the stress at the yield point 17·49 tons per sq. in., and at the breaking point 26·17 tons per sq. in.

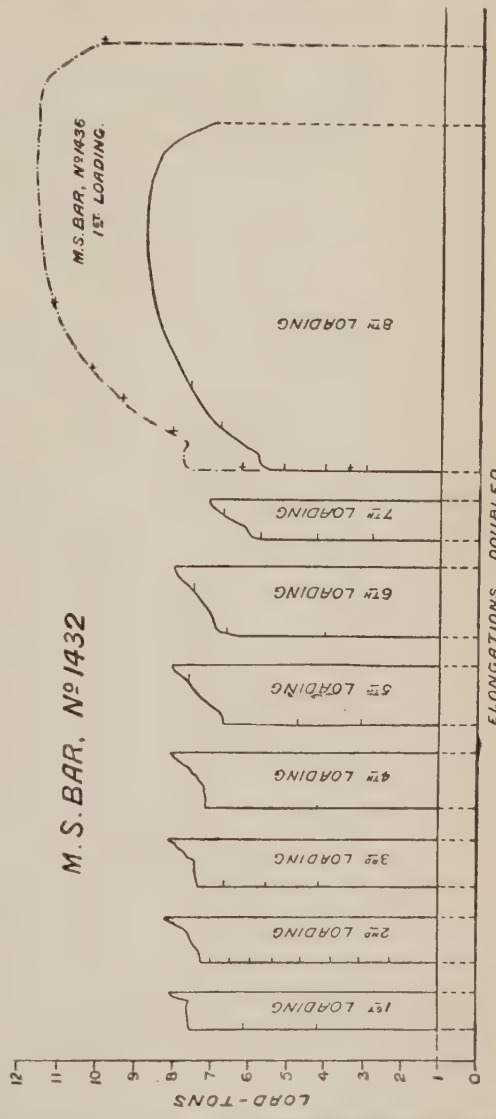


Fig. 62.

[1] Unwin, *Proc. Royal Society*, vol. lvii, 1894.

It is clear from these tests that the change produced in the iron or steel bar by straining beyond the yield point is almost completely reversed by simple annealing, and this apparently after any number of repetitions of the process.

81. *Bairstow's Research on the Elastic Limits of Iron and Steel, under Cyclical Variations of Stress.*[1]—A very important research has recently been carried out at the National

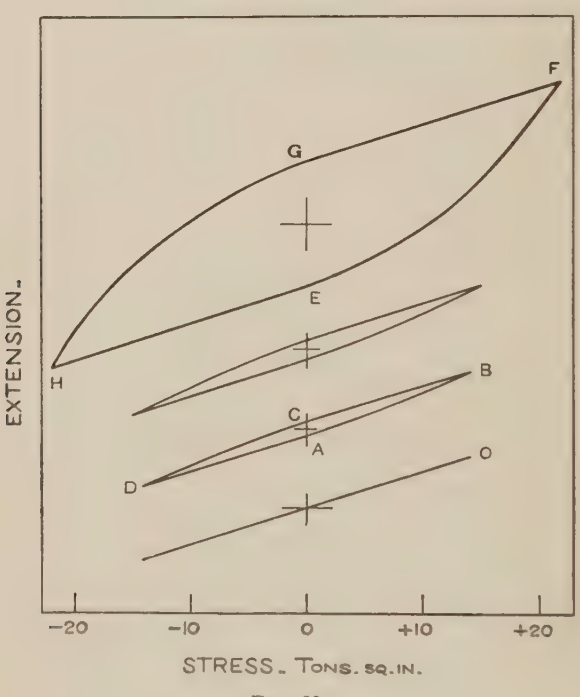


FIG. 63.

Physical Laboratory. The test bars were very small, the gauge-length being 0·5 in. and the cross-section 0·025 to 0·05 sq. in., but the measurements of deformation were exceptionally accurate. A testing-machine was constructed such that the test bar could be strained through any definite range, repeated as often as required. The extensometer was permanently installed, so that the deformations could be observed throughout the whole period of the experiment.

[1] *Phil. Trans. of the Royal Society*, A., vol. 210, pp. 35–55.

Only a very abbreviated account can be given of some of the results, the memoir is very suggestive and should be consulted.

Case I.—A bar of axle steel was subjected to equal tensions and thrusts, of ± 14·1 tons per sq. in., exceeding the natural elastic limits, but less than the primitive elastic limits. Fig. 63, o shows the stress-strain diagram during the earliest repetitions. It is a straight line showing that the bar during this period was perfectly elastic. Gradually, however, a hysteresis loop developed and increased, the curve A B C D being obtained after 18750 repetitions. The vertical width of the loop, greatest at the mean stress, is a set which appears and disappears during a cycle and is termed by Bairstow the *cyclical set*, to distinguish it from a permanent elongation of the bar. The curve is traced in the direction A B C D, and the parts B C, D A are straight and parallel to the line o. Increasing the stress to ± 15·0 tons per sq. in. caused an increase of the width of the hysteresis loop, that at 23260 repetitions is shown. Finally with stresses of ± 20·2 tons per sq. in. and at 29280 reversals the large loop was obtained. Mr. Bairstow believes that with a slightly lower range of stress, probably ± 13 tons per sq. in., the bar would have remained perfectly elastic and no hysteresis loop would have been developed.

Case II. *Unequal Stresses.*—A bar of axle steel was subjected at first to stresses ranging from − 8·3 to + 18·3 tons per sq. in. Hysteresis loops developed as in the last case. Keeping the maximum stress the same the lower limit of stress was changed to − 9·7, − 12, and − 15·7 tons per sq. in. As the range of stress increased the width of the hysteresis loops, that is the cyclical sets, increased. But in addition in this case there was a gradual lengthening of the bar, or increasing permanent set. The rate of increase of permanent set diminished with the increase of the repetitions, and became very small or zero with repetition of loading.

To determine the natural elastic limits, Bairstow proceeds thus. The cyclical sets in tests, with ranges somewhat greater than the range of perfect elasticity, are plotted as ordinates with ranges of stress as abscissæ. These points lie on a straight line which produced, intersects the axis of range of stress at a point which measures the range for which the elasticity is perfect. These ranges will be mentioned in the chapter on Repetition of Stress.

CHAPTER VI

TESTING-MACHINES

82. A TESTING-MACHINE is simple or complex according as it is intended for a few or a greater number of purposes. If the machine is to be used for determining the quality of one kind of material subjected to one kind of straining action, it may be of very simple construction. In that case it will be desirable that all the test pieces should be of one size and form, and this simplifies the construction of the machine. If, however, a testing-machine is to be used for varied investigations, on many materials, under different kinds of straining action, for specimens of different shapes and sizes, then the machine must be more complicated, and accessory apparatus must be provided. In the adaptation of a machine to diverse purposes there must be some sacrifice of convenience, some compromise between conflicting requirements. Hence, there is no testing-machine absolutely preferable to all others. Almost every form of testing-machine has special merit for some particular kind of work.

It must be remembered that, with every increase of complexity and size in the machine, and with every addition to the accessory apparatus, greater difficulty in using the machine, more care in adjustment, and more loss of time in adapting it to particular experiments is involved. Hence, the extent to which it is desirable to combine different functions in a single machine is a matter for careful consideration in any given case. Some testing-machines are like special tools in a workshop, doing one kind of work only, and with these the rapidity of work is greatest, and the liability to errors of oversight or ill-adjustment is least.

The simplest mode of testing is to apply a dead load directly to the test bar. Many of the earlier experimental investigations were made in this way, and the method is still used in testing the weaker materials. It is, however, laborious and inconvenient to have to handle a load equal to the

straining action required. By using a lever between the load and specimen, the weight to be handled is diminished in the ratio of the lever arms. Many of the earlier testing-machines were little more than a lever for applying the stress. But here a practical inconvenience arises. If the specimen is held between a fixed abutment and the lever, the position of the lever alters as the specimen deforms, and so much the more the greater the ratio of the lever arms. Some arrangement must be made for neutralising the effect of the deformation. The abutment must be moved to keep the lever horizontal. In some machines a screw and nut afforded the only means of adjustment. In these cases it was usually necessary to remove or reduce the load while adjustment of the abutment was made.

To escape some of the difficulties of a lever arrangement a hydraulic press has been used to produce the stress in the specimen. The specimen being held at one end by a fixed abutment, the other is strained by attachment to the ram of the press, the movement of which takes up the deformation. In such machines the stress in the specimen must be inferred from the fluid pressure on the plunger, indicated by a pressure-gauge, and an allowance must be made for the friction of the cup-leather or packing of the ram.

According to experiments of Mr. John Hick, the friction of a press cup-leather on a ram d inches diameter, with a pressure of p lbs. per sq. in., is—

$$\text{F} = \text{C}\, d\, p,$$

where C is a constant for a certain range of the values of p. But the whole fluid pressure on the ram is $\frac{1}{4}\pi d^2 p$. Hence, the fraction of the load on the ram expended in friction and not transmitted to the specimen is $4c/\pi d$; that is, it decreases as the diameter of the ram is greater. Hence the proportional error due to miscalculation of the friction is less as the size of ram increases. Other experiments show that the friction is a smaller fraction of the total load on the ram as the pressure per unit area is greater.[1]

[1] According to the experiments of Mr. Hick, the constant $c = 0{\cdot}03$ to $0{\cdot}05$ when p is in lbs. per sq. in. and d in ins. Hence the friction in per cent. of the load on the ram is—

For d =	6	12	18	24	30	36
When c = 0·03	0·64	0·32	0·21	0·16	0·13	0·11
When c = 0·05	1·06	0·53	0·35	0·26	0·21	0·18

These values are only applicable, however, for very large pressures in the

It next appeared possible to combine the advantages of the hydraulic press machine and the lever machine in this way. The test bar was placed between a hydraulic press and a lever, or system of levers, acting as a steelyard. Roughly speaking, it may be said that in such a machine the stress is applied by the hydraulic press and measured by the steelyard. Most modern machines are essentially arranged in this way, though in some screws and gearing are substituted for the hydraulic press, and in others a manometric arrangement is substituted for the steelyard.

83. *Machines for Testing in Various Ways Iron, Steel, and other Strong Materials.*—Machines for general testing purposes almost always now consist of—

(1) A lever, or system of levers, with weights, forming a complete weighing apparatus. This is connected with one end of the specimen, and its purpose is to indicate from moment to moment the exact stress applied to the specimen. In a few cases, in place of the lever and weights, a manometric apparatus is employed, the stress being balanced by fluid pressure, which is measured by a mercury column or a pressure-gauge, or in Emery machines by a lever system.

(2) A system of shackles for holding the specimen to be tested, so guided that the straining action is exactly of the kind required. Shackles must be provided suitable for the different sizes and forms of specimens to be tested, and

ram cylinder. At lower pressures the friction is a much larger fraction of the load. The author tested the friction of the cup leather of an hydraulic press having a ram 36 ins. in diameter on two different occasions, using copper crusher cylinders. The results were as follows:

	Pressure in press cylinder, lbs. per sq. in.	Total load on ram, in tons.	Effective effort of ram, in tons.	Friction, in tons.	Efficiency, per cent.
I	50	25·2	19·2	6·0	0·762
	110	55·5	45·8	9·7	0·826
II	50	25·2	21·3	3·9	0·845
	110	55·5	50·3	5·2	0·907

These results, so far as they go, agree with the relations—

$$P = (0{\cdot}92\,p - 9)\,a \quad \text{I}$$
$$= (0{\cdot}99\,p - 7{\cdot}5)\,a \quad \text{II}$$

where P is the effective thrust of the ram in lbs., p the pressure in the cylinder in lbs. per sq. in., and a the area of the ram in sq. ins.

different shackles for each different kind of straining action to be applied.

(3) To neutralise the effect of the deformation of the specimen on the position of the weighing apparatus, a movable abutment must be provided to hold one end of the specimen. This is most commonly the ram of a hydraulic press, which can be actuated by a pump, a screw compressor, or an accumulator. In other cases, worm-gearing acting on a nut and screw has been used. The object of all these arrangements is to take up regularly and smoothly the deformation of the specimen, so that the point of attachment of the weighing apparatus is practically immovable.

With regard to their general arrangement, testing-machines may be divided into—(*a*) Horizontal testing-machines, in which the stress is exerted horizontally; and (*b*) Vertical machines, in which the stress is exerted vertically. The difference is one of convenience chiefly. Where very long specimens have to be tested the machine must be horizontal. In horizontal machines the weight of the shackles and other parts connected with the specimen acts transversely to the load applied to the machine. If not neutralised by guides the weight would produce straining actions not measured by the weighing apparatus, and the guides themselves introduce some frictional resistance which gets measured as part of the stress. In vertical machines, on the other hand, the weight of the shackles acts in the direction of the load, and can be balanced so as not to affect the measurement of the stress.

84. In designing a testing-machine the qualities to be aimed at are as follows:

(1) The machine must have adequate sensitiveness—that is, the power of indicating decisively and accurately small differences of stress. To obtain sensitiveness in a lever machine, the fulcrum on which the lever rests and the supports of the shackles and weight are hard steel knife-edges acting on hard steel planes. The sensitiveness depends on the smallness of radius of the knife-edges and their accurate straightness. If initially, or under the action of the load, the knife-edge bends, it virtually becomes broader, and the sensitiveness is diminished. Now, the amount of sensitiveness required in a good machine is not a quantity which can be definitely assigned, nor is it easy to measure in an actual machine, except in the case of an unloaded

machine. But there is no doubt that the sensitiveness attained in good machines is in excess of practical requirements. It may be pointed out that two specimens cut from the same plate quite commonly differ in strength by more than 1 per cent. Supposing the strength of the test bar to be 20 tons, 1 per cent. of this would be 4 cwt., and a reasonably good machine tolerates differences of stress of far less amount than this. In most machines the sensitiveness varies with the load and increases as the load is greater. That is, the additional stress required to distinctly move the weighing apparatus becomes a less fraction of the load as the load increases. In a good testing machine, carrying its full load, the lever will be distinctly moved by an addition to the stress of $\frac{1}{10}$ ton. That is, the sensitiveness is such that $\frac{1}{200}$ of the load is indicated. This is equal to the sensitiveness of a good chemist's balance. The sensitiveness of machines with manometric apparatus may be made still greater.

(2) The machine must be accurate to the indications given—that is, the stress indicated by the machine must differ very little from the real stress. A sensitive machine may be inaccurate if the ratio of the leverage is imperfectly known, and it must be inaccurate if, from any defect of the parts, the leverage changes with the load. Hence, it is of much more importance than has generally been supposed that a testing-machine should be so arranged that it can easily be tested. The weights used to load the lever can, of course, easily be standardised. But in many machines the leverage, or ratio of the weight applied to the stress on the specimen, has only been determined by measurement of the distances between the knife-edges, and the original determination of the leverage by the maker is accepted as sufficient, however long the machine may have been in use. It is clear that the wear or displacement of the knife-edges may seriously alter it in course of time. If the fulcrum distance is 2 inches, a displacement of $\frac{1}{20}$ inch would introduce an error of 1 per cent. into all measurements made by the machine on the assumption that the leverage had remained constant.

Testing the accuracy of a machine by dead weights is in principle the most satisfactory method, but it can only be applied for very moderate loads. There are two methods of determining the relative accuracy of two machines: (*a*)

to measure the extensions of a standard test bar, (b) to measure the compressions of soft copper cylinders.

(3) Facility of adjustment for different kinds of straining action, and for specimens of different dimensions. The importance of this quality in a machine depends very much on the kind of work it is intended to do. But the changes used for different kinds of stress are somewhat costly and cumbrous, and the operation of changing the apparatus for various kinds of work is somewhat laborious.

(4) Capability of easy and rapid manipulation during a test. In commercial testing it is of importance that the testing should be accomplished rapidly. The means of gripping the specimen must be convenient, and the manipulation of the weighing and hydraulic apparatus can best be effected by engine power.

(5) Autographic apparatus for registering the results is very convenient, and is a safeguard against errors in recording the results. Some machines are better adapted than others for the addition of autographic apparatus.

(6) It is very objectionable if, during a test, the specimen is subjected to shocks and vibrations. These may arise either in the weighing apparatus (in adding loads, for instance); or in the hydraulic press (by the action of a pump); or, lastly, from the energy acquired by parts of the machine which move when the specimen more or less suddenly takes an increment of deformation.

Suppose a cubic inch of water suddenly forced into the hydraulic press by the pump. If the lever and weights had no inertia, no harm would result. But, in fact, the movement of the press ram induces a movement of the whole system, and the stress in the specimen is for the moment governed by the inertia of the whole system connected with it. If the specimen suddenly extends a little, the weights on the lever move through a not inconsiderable distance. They acquire energy in falling, which again is expended in momentarily increasing the stress on the specimen.

The question whether a machine with small leverage or large leverage is likely to produce greater stress in the specimen in consequence of its inertia has been a good deal discussed. If a specimen is loaded with a dead weight W the inertia of the load reckoned at the specimen is W. But if the same specimen is put in a machine with a leverage n, with a load W/n producing the same stress, the inertia of the load

reckoned at the specimen is $(M/n)n^2$, or M/n. Hence it has been argued that the stresses due to shock increase directly as the leverage of the machine. All that the calculation shows is that, with a given velocity of movement at the specimen, the stored energy of the load liable to be expended in straining the specimen increases with the leverage. But the inference ignores the practical conditions in which testing-machines are used. In proportion as the leverage of a machine is greater, its movements are more narrowly limited by the stops at the free end of the lever. The greater the leverage the more easily is any tendency to acquire velocity in the machine detected and controlled. Hence, it is probable that the greater the ratio of the leverage, the less is the liability to unknown and prejudicial stresses due to inertia of the machine. In skilful hands, each machine is used in a manner suited to its construction and so as to reduce any action of this kind to a negligible amount.

85. *Arrangement of the Lever or Steelyard and Weights.*—In the oldest form of lever machine a bent lever (fig. 64) was

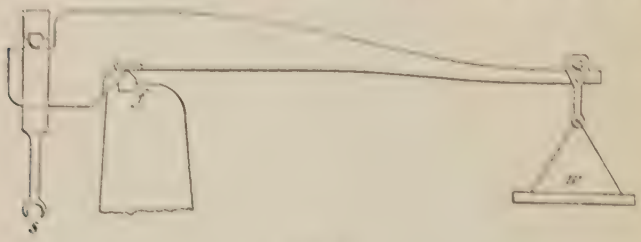


FIG. 64.

used, the three principal knife-edges being nearly in one straight line. The object of this arrangement was to secure a constant leverage, notwithstanding some change of position of the lever. The leverage is the ratio of the perpendiculars from the fulcrum f on the directions of the load w and stress s, and if the knife-edges are not in one straight line the ratio of those distances sensibly changes with the alteration of inclination of the lever. In more modern machines the lever is left straight, and is formed of sufficiently rigid side plates (fig. 65), between which are the knife-edges, fixed in rigid cross supports.

In the older machines and in some modern machines the loading is effected by placing separate weights in a scale-pan. Unless the leverage is large this is laborious and, unless the

lever is supported when weights are added, shocks are produced on the specimen. Two modes of overcoming this

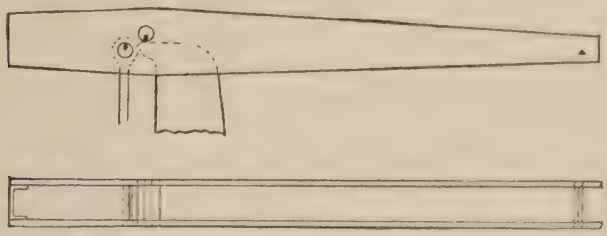


Fig. 65.

difficulty have been found. In one the separate weights are successively added by mechanical arrangements; in the other a single travelling, or jockey, weight is rolled out along the

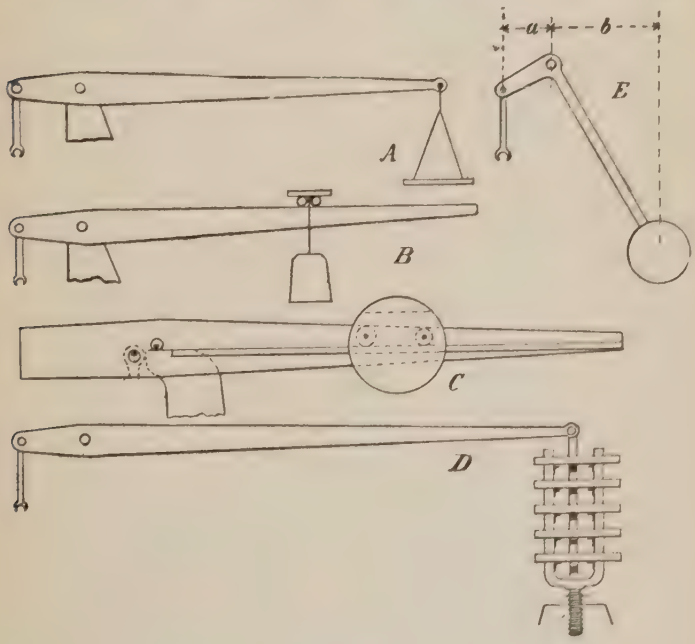


Fig. 66.

lever. In the former, the leverage is constant; in the latter, the leverage varies as the jockey-weight is rolled out.

Fig. 66 shows diagrammatically these arrangements. At

A is the ordinary lever and scale; B and C are two arrangements in which jockey-weights are used. In C the weight is so contrived that its centre of gravity lies in the line through the knife-edges. In order that the variation of position of the lever may not affect the stress on the specimen, the centre of gravity of the lever must be on the line through the knife-edges, and the jockey-weight must either have its centre of gravity on that line, or must be hung from a knife-edge which travels on that line. At D is shown the mechanical arrangement for adding weights to the lever. The weights are carried by a frame which can be raised or lowered by a screw. As the frame is lowered the weights are deposited in succession on projections upon the rod connected with the lever.

FIG. 67.

In fig. 67 this mode of carrying the weights is shown in more detail. The central rod a is suspended from the lever. The side rods b, b are connected with a screw raising or lowering arrangement; w, w are the carefully-adjusted weights. When not in use the weights rest on lugs on the side rods, b, b. By lowering b, b the weights are successively dropped without shock on the corresponding lugs on a.

There is one other arrangement of the lever which should be mentioned. In the testing-machines of Thurston, Michaelis, and Polmeyer, a bent pendulum lever is used (E, fig. 66), carrying a single heavy load. As the pull on the specimen is increased, the pendulum-bob moves outwards and upwards. If a and b are the perpendiculars from the principal fulcrum on the directions of the load and stress, the varying leverage is the ratio b/a.

86. *Principal Types of Testing-machines.*—It will be seen that the most obvious arrangement is to place the weighing apparatus at one end of a specimen and the straining apparatus at the other. In fact, most machines are thus constructed. Later, it appeared that certain advantages were obtainable by placing both weighing and straining apparatus at the same end of the specimen.

The simplest arrangement is that shown in fig. 68. In this machine the specimen *s* is held between a shackle attached to a horizontal weighing lever above and the ram *p* of a hydraulic press below. The weighing of the stress is effected by rolling out a jockey-weight *w* along the lever, or, in the Martens machine, by the arrangement shown in fig. 67.

Somewhat similar is the arrangement of the testing-machine of Messrs. Fairbanks & Co., of New York (fig. 69).

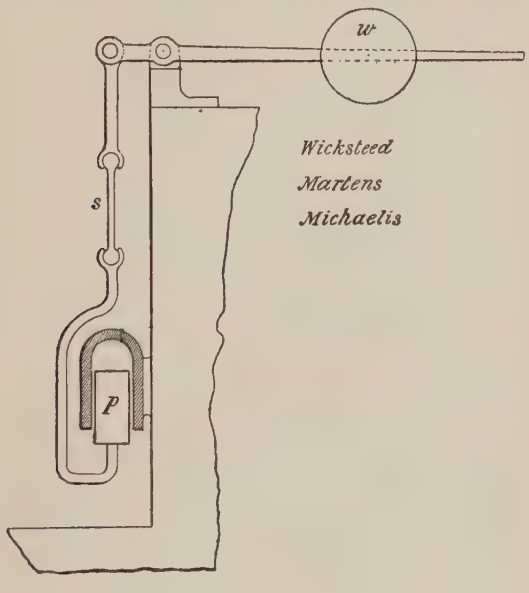


Fig. 68.

In this case a worm-wheel and screw are substituted for the press. The Fairbanks machine is virtually an ordinary platform weighing-machine adapted to the purpose of testing. But, instead of the simple-lever system shown in this diagram, the actual machine has a compound-lever system, involving the use of numerous levers and knife-edges, the object being to gain so great a leverage (in some cases 24,000 to 1) that the stress is balanced by very small weights. Fig. 70 shows diagrammatically the Thomasset machine, in which a manometric arrangement *d* is substituted for the weights used in other machines. The end of the lever presses on what is

usually a flexible diaphragm supported by fluid pressure. A pressure-gauge or mercury column, indicating the amount of fluid pressure on the diaphragm, gives data for determining the stress when the area of the diaphragm and leverage is known.

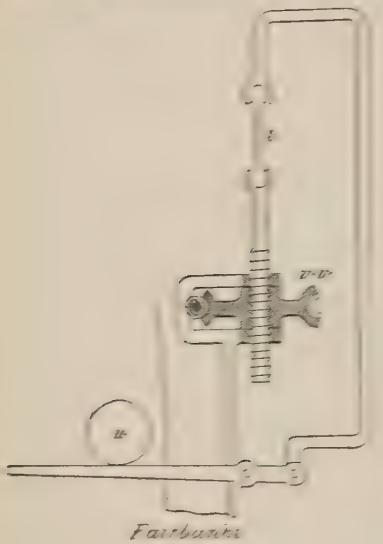


Fig. 71 shows the machine of the Gebrüder Company at Mulhouse, which has a peculiarity adopted in the testing-machines of Riehle Bros., extensively used in America. In order to get a very short knife-edge distance on the main lever, the fulcrum is not placed in the lever itself but in a subsidiary lever below,

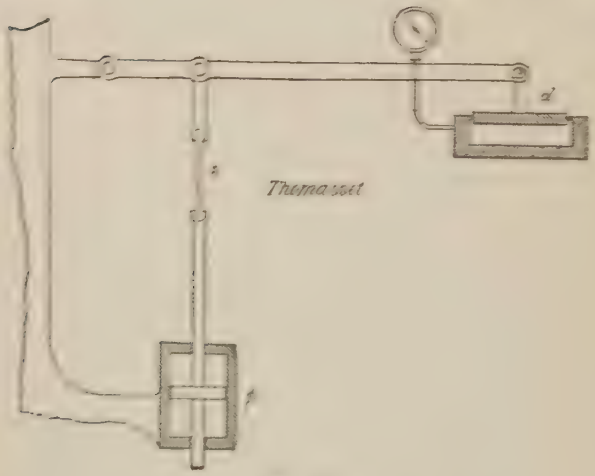


Fig. 70.

connected to the main lever by links. The distance a is the virtual fulcrum distance, or the short arm of the lever. It

is obvious that this may be made as small as desired without introducing any mechanical difficulties of construction.

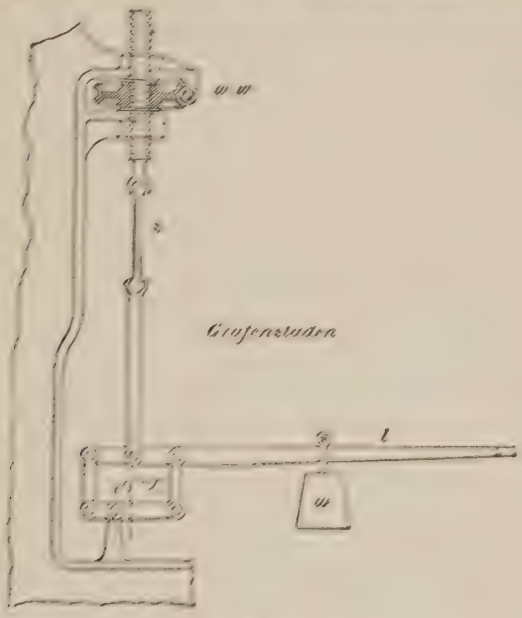


FIG. 71.

Fig. 72 shows the arrangement of the horizontal testing-machine of Messrs. Greenwood & Batley, of Leeds. It gives a horizontal pull, and has a compound-lever system. This involves the use of a knee lever between the weighing lever and specimen.

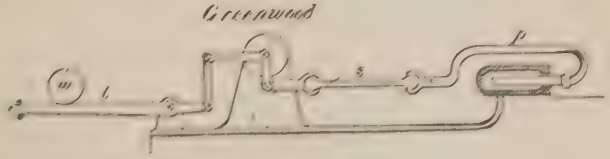


FIG. 72.

Fig. 73 is a sketch of the horizontal Mallard machine, in which manometric arrangements are substituted for a lever system.

Fig. 74 shows the Werder machine, which has been adopted very extensively in Germany. This differs from all

the preceding machines in this, that both the weighing and straining apparatus are at one end of the specimen. Hence, the expensive parts of the machine being all at one end, arrangements can be made to take in specimens of almost any length, by prolonging the bed of the machine, without much extra expense. In the Werder machine the hydraulic press

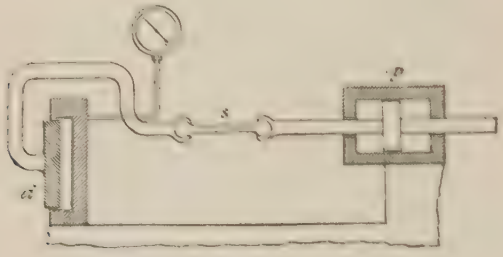


FIG. 73.

acts on the short arm of a single bent lever *l*. This lever is carried by the specimen, so that the other end of the specimen requires only a fixed abutment. By the action of the press the lever is kept horizontal, notwithstanding the deformation of the test bar. The Werder machine may be described as a machine in which the principal lever is supported on a

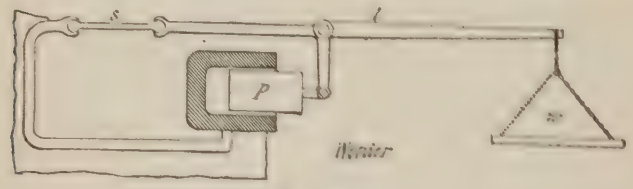


FIG. 74.

moving fulcrum. The great advantage of having only a fixed abutment to provide for the back end of the specimen is obvious.

EARLY TESTING MACHINES

87. *The Woolwich Dockyard 100-ton Machine.*—This machine is described and figured in the first edition of Barlow's 'Strength of Materials,' and must therefore have

been constructed at a very early date.[1] It was intended chiefly for testing cables, but was used for ordinary testing also. Barlow describes its principle thus: — 'The Admiralty have had constructed in Woolwich Dockyard for testing iron cables a machine in which the strain is brought on by hydrostatic pressure, but its amount estimated by a system of levers, balanced on knife-edges, which act quite independently of the strain there is on the machine, and exhibit sensibly a change of pressure of ¼ ton, even when the total strain amounts to 100 tons.' The machine, which was constructed by Bramah, had a horizontal cast-iron frame of 104½ feet in length. On one end of this was a hydraulic press, the position of which could be adjusted by gearing. At the other end was a system of levers, taking the pull and weighing it. The first lever was a bell-crank lever, as in most horizontal testing-machines, and there were two other levers. The total leverage was 2,240 to 1, so that 1 lb. in the scale-platform balanced 1 ton of stress. The hydraulic press was worked by pumps, arranged with great ingenuity to suit the varying pressure required. Friction-grip shackles are shown for ordinary test bars, to which reference will be made later. The distinctive features of this machine reappear in all modern testing-machines.

Fairbairn's Machine.—The testing-machine constructed by Fairbairn, and used in many of Eaton Hodgkinson's experiments, consisted of a heavy wrought-iron lever, with arms in the ratio of 8 to 1 and of the bent form (fig. 64). The lever rested on a short knife-edge at the top of a box-shaped casting, and at its free end carried a scale-platform. There was no hydraulic press, and the deformation of the specimen was taken up by a nut on a screwed rod. The lever was used in several ways both for tension and crushing.[2]

Machine of Major Wade.—In tests of cast iron for guns in America, in 1855, a machine was used designed by Major Wade,

[1] *Treatise on the Strength of Timber and Iron*, by P. Barlow, F.R.S., London, 1837, p. 237.

[2] This lever machine, which has a certain historical interest from the importance of some of the researches made with it, is figured in its original form in Fairbairn's paper, 'The Strength of Wrought-iron Plates and Riveted Joints,' *Phil. Trans.* 1850; *Useful Information for Engineers*, Fairbairn, p. 252. The same machine, somewhat altered in arrangement, and in the form in which the author often used it between 1855 and 1865, is figured in a paper, 'The Strength of Iron at Different Temperatures,' *Brit. Assoc. Report* for 1856.

and a similar machine was used for many years at Woolwich. It is chiefly noticeable for being one of the first compound-lever machines. One lever had a ratio of 20 to 1, and the second lever, to which the specimen was attached, a ratio of 10 to 1. Consequently, the loads on the specimen were two hundred times the applied weights. It was only adapted for very short specimens.[1]

Machine at St. Chamond, for tensions up to 50 tons.[2] This rather remarkable single-lever machine has some peculiarities adopted in more modern machines. The lever is constructed of two I-beams of wrought iron, about 14 feet long and 12 inches deep. A rigid knife-edged bar fixed between these side beams rests on the top of a strong iron standard. At 0·6 inch only from the fulcrum knife-edge is the knife-edge supporting the shackle. The lever is prolonged backwards, and carries a counter-weight for putting it in balance initially. A travelling jockey-weight runs along the lever, and balances the strain in the specimen. A peculiar arrangement is adopted to take up the deformation and keep the lever horizontal. This is a wedge, sliding in guides, and driven by a screw and gearing.

SINGLE-LEVER MACHINES

88. *The Werder 100-ton Testing-machine.*—In 1852 a testing-machine was designed for the Railway Commission of Bavaria by Ludwig Werder, and constructed by Messrs. Klett & Co., of Nuremberg. A number of Werder machines are in use in Germany. Probably by far the largest part of the original mechanical investigations carried out before 1895 has been accomplished by the aid of Werder machines. In the hands of Dr. Bauschinger, of Munich, tests of materials have been made with this machine with a precision and accuracy never before attained.

The Werder machine is a horizontal testing-machine, with hydraulic press worked by pumps and single-lever weighing apparatus. By an ingenious arrangement the press and lever are kept on the same side of the specimen. All the complicated and expensive parts of the machine being thus

[1] *Report on Metal for Cannon*, by the American Ordnance Department, pp. 305, 315.

[2] MM. Denizeau and Lechien, *Mémorial de l'Artillerie et de la Marine*, 1883.

brought to one side of the specimen, comparatively simple and inexpensive arrangements can be made for extending the machine to take in specimens of very great length. Usually the Werder machine is made to test specimens both in tension and compression up to 30 feet in length.

Fig. 75 shows a sectional elevation of the more important working parts, and detailed drawings will be found in the treatises cited below.[1] R is the hydraulic press ram, which acts against a knife-edge on what is really a bent lever L_1. The crosshead C_1, which holds one of the shackles S_1, is connected by the long bolts *t*, *t* with a crosshead carrying the other knife-edges which support the lever. If the specimen stretches, C_1 moves to the right, and the lever falls; if the press ram is then moved to the right the lever is again lifted. The back crosshead C_2, which holds the other shackle S_2, slides on cast-iron guides. It is spaced at any distance from the fixed frame of the machine by the loose distance pieces *d*, *d*.

At *s* is a tension test bar, and *m* is Bauschinger's mirror arrangement for measuring extensions. In testing, weights are placed on the scale-platform of the lever L_1,

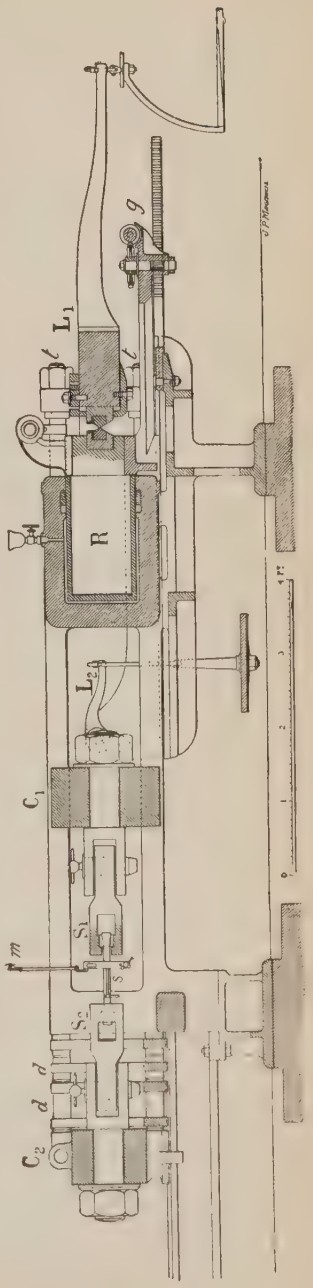


Fig. 75.

[1] *Mittheilungen a. d. mechanisch-technischen Laboratorium in München*, Heft 1 und 3. *Maschine zum Prüfen der Festigkeit der Materialien und Instrumente zum Messen der Gestaltsveränderung der Probekörper.* München, 1882. Also, Lebasteur, *Les Métaux.*

and then by the pumps the ram R is moved out till the lever is in balance.

To obtain a high ratio of leverage, so that the weights to be handled may be small, the short arm of the lever L_1 is reduced to the extraordinarily small distance of 4 mm. or $\frac{3}{16}$ inch. The lever is of such a length that the leverage is 500 : 1. Of course the short-arm length of the lever cannot be directly measured with accuracy enough to determine the leverage of the machine. Hence a second lever (control-lever) L_2 is provided, acting on the crosshead C_1. This lever has a ratio of 10 : 1, and its arms can be accurately measured. By putting weights acting on L_2 in balance with weights acting on L_1 the leverage of the principal lever L_1 is determined. With so small a fulcrum distance as $\frac{3}{16}$ inch the width of the knife-edges is a quantity comparable with the short-arm length of the lever. It is necessary, therefore, that the lever L_1 should have an extremely small range of motion. This is secured by placing a spirit-level on the lever. *g* is hand-gear for returning the press ram after a test.

The arrangement of the hydraulic press and lever will be better understood from the diagrammatic sketch, fig. 76. Here R_1 is the press cylinder cast in one with the frame of the machine, and R_2 is the press ram. The press ram, cased in gun-metal, is 12 inches diameter. The hand-pumps for working the press have rams of 1·2 and 0·4 inch diameter. The ram R_2 carries a horn *a*, with cross-shaft, from which the great lever L_1 is suspended by links, and also the crosshead C connected with the front shackle. The back part of the lever L_1 is a large U-shaped casting, partly surrounding the press, so that the centre of gravity is near the knife-edges. It carries a scale-platform and adjusting weight. The pair of crossheads C pass through the lever, and are connected each by two longitudinal tie-rods *t* to the shackle crosshead. The press ram carries in front a hard steel prism 14½ inches long, against which one knife-edge on the lever acts. The crossheads C each carry a prism 7⅝ inches long, against which the other knife-edges act (shown dotted). The distance between the upper and lower knife-edges, reduced to $\frac{3}{16}$ inch in the actual machine, is the short-arm length *h* of the bent lever, the long arm being *l*.

Fig. 75 shows the arrangement of the machine for testing bars in tension. For crushing cubes and short specimens the

space between c_1 and the back of the press is utilised, proper seatings being introduced. Longer specimens can be crushed between c_1 and c_2, the tie-bars t, t being then extended to the crosshead c_2. Convenient arrangements for transverse testing and for torsion are also easily fixed.

89. *Vertical Testing-machine of Messrs. Buckton & Co., of Leeds.*—This machine was described at the Leeds meeting of

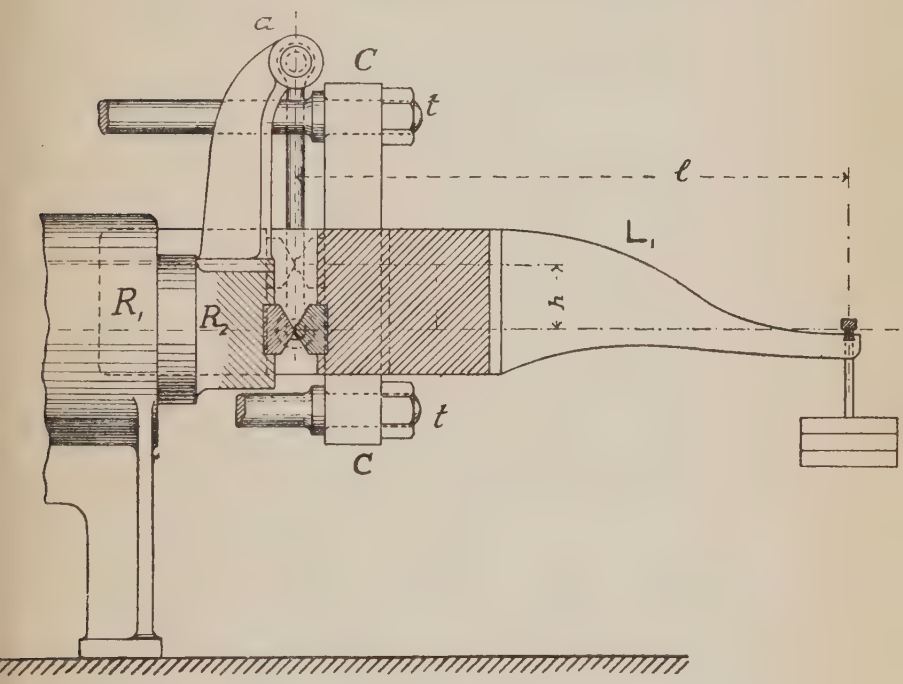


Fig. 76.

the Institution of Mechanical Engineers.[1] The machines then constructed were 50-ton machines for testing ordinary short commercial test bars. It appeared to the author, in 1883, that a larger machine, capable of taking in moderately long specimens, could be designed on the same general plan. In correspondence with Mr. Hartley Wicksteed, plans were made for a 100-ton machine, which would take specimens 6 feet long. Two very satisfactory machines were built of

[1] *Proc. Inst. of Mech. Eng.*, 1882.

this size, under the author's direction, for the engineering laboratories at Cooper's Hill and at the Central Technical College of the Guilds Institute of London. Other machines of the same power and somewhat different details have since been made.

Fig. 77 shows the general arrangement of the 50-ton Buckton machine. H is a rigid cast-iron standard bolted to the foundations, and having at top a horn projecting back to carry the principal knife-edge or fulcrum of the lever. The great lever L, L, with its jockey-weight W, forms the weighing apparatus, and the hydraulic ram R, R takes up the deformation of the specimen. A tension specimen is shown at S, between the friction-grip shackles A, B. The knife-edges of the lever L, L are 3 inches apart, one resting on the standard H, the other supporting the shackle A. To support the knife-edges and prevent flexure, they are gripped by rigid castings bolted between the side plates of the lever. The hydraulic press P has a stroke of 6 inches to take up elongation and slip of the test bar in the grips. The press is worked by means of a 'quiet compressor.' This is a press with a ram driven by a pair of screws, which again are driven by gearing and belting. This secondary press, which is a substitute for the pumps ordinarily employed, forces water into the main press P quietly and without shock, and works very satisfactorily indeed. The press is so used that the lever is kept 'in balance'—that is, floating freely between the stops which limit its motion. The jockey-weight weighs exactly one ton, and can be moved along the lever by a screw driven at will, either by belting or by the hand-wheel in front of the standard. Before a test the jockey-weight is run back till the lever is in balance with the test bar free. A vernier, attached to the jockey-weight, is set to zero on a scale running along the lever. Then the specimen is fixed, and the jockey-weight moved out along the lever, while the press is used to keep the lever horizontal. Each 3 inches of movement of the jockey-weight adds a ton to the load on the specimen, and the vernier easily reads on the scale to $\frac{1}{100}$ ton.

90. *100-ton Vertical Testing-machine of Messrs. Buckton & Co.*—The photographic frontispiece shows a general view of the engineering laboratory at the Central Technical College, with the 100-ton testing machine. Plate II. is a general elevation of the same machine. F, F is the main

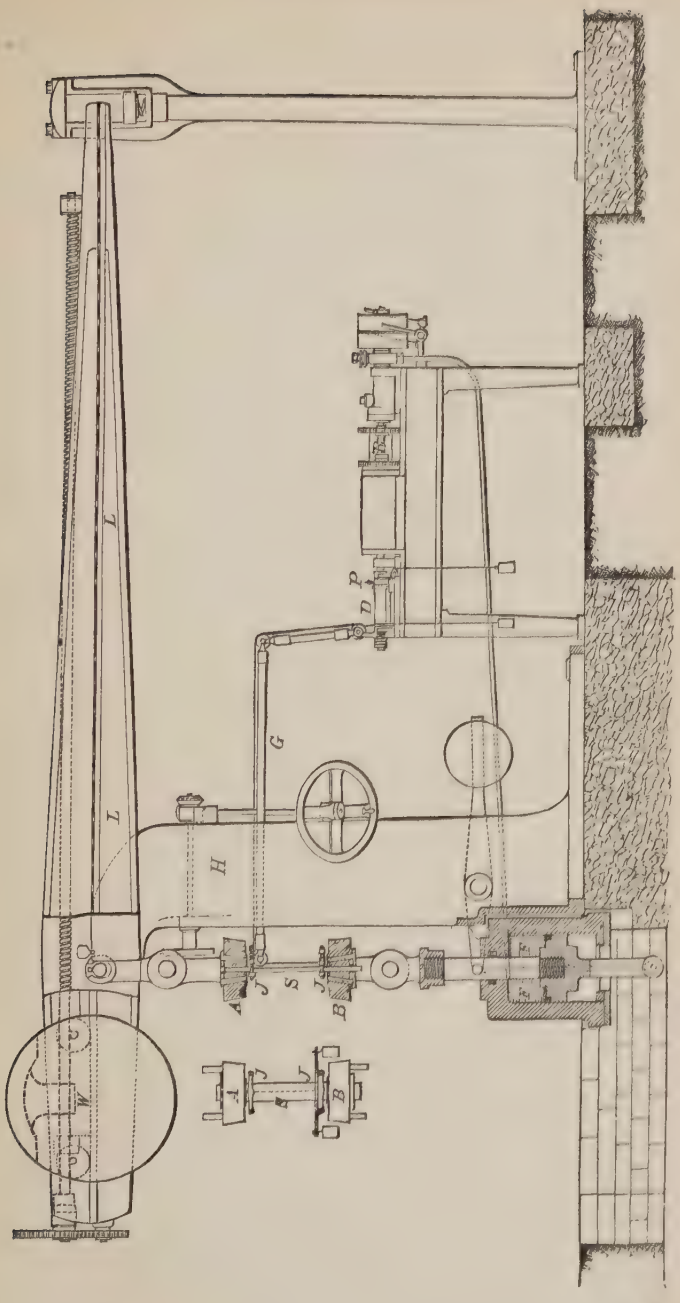


FIG. 77.

standard of such a height that moderately long specimens can be tested. To the foot of this standard is bolted the principal hydraulic press R, the ram of which acts downwards on a crosshead c_1, connected by adjusting side screws to an upper crosshead c_2, to which the lower specimen shackle s_2 is attached. There is worm-gearing to the side screws to adjust the length between the shackles s_1, s_2. The press ram is kept home by the balance-weight B, attached to it by spring shackles. To work the press there is a second press or compressor C, the ram of which is driven by the twin screws s_2 and gearing g_2. The crossed belts b_2 and fast-and-loose pulleys behind the standard drive the compressor ram in or out, and so force water into or allow it to flow back from the main press R. r_2 is a hand-lever to the fork actuating the belts b_2, which drive the compressor.

The great main lever L, of steel side plates, rests on the top of the standard F, F by means of a knife-edge, and a second knife-edge behind this supports the upper shackle s_1. These knife-edges are 20 inches long, and are formed of hardened steel ground into a rectangular groove in steel bars 4 inches in diameter. These bars are further supported by castings bolted to the side plates. The distance between the knife-edges is 4 inches. The free end of the lever plays in a space in the supporting pillar P. J is the jockey-weight, weighing one ton,[1] and straddling the lever so that its centre of gravity is as nearly as possible on the plane through the knife-edges. This runs on four rollers on rails fixed each side of the lever, and is moved by the long screw s, s. The jockey-weight can be put in motion either by the cross-belts b_1 connected with the reversing handle r_1, or by the hand-wheel h and countershaft k, if very slow motion or fine adjustment is required. Along the lever is the graduated scale a, a, and a vernier v on the jockey-weight indicates the position of the jockey-weight. Initially the lever is put in balance, and the vernier set to read zero on the scale. Then each 4 inches the jockey-weight moves adds a ton of stress on the specimen. The scale is 200 inches long, so that with the jockey-weight at the end of the lever a stress of 50 tons is measured. For greater stresses the jockey-weight is run back to zero, and the 25-cwt. load W is attached to the lever by a screw coupling. As this hangs at

[1] In later 100-ton machines a 2-ton jockey-weight has been used and the extra load W dispensed with.

a levérage of 40, it balances a stress of 50 tons. The jockey-weight is then run out again. The vernier easily reads to $\frac{1}{200}$ ton.

The tension shackles s_1, s_2 are shown in place, and will be described in a later chapter. The lower crosshead is guided by a slide on the frame F, F. For compression tests a table guided by the same slide is hung from the upper knife-edge by four long suspension rods, and specimens are crushed between this table and the lower side of the crosshead c_2.

It will be seen that, standing by the standard, the experimenter has complete control of the machine. The specimen is in sight on the left; the floating of the lever can be seen

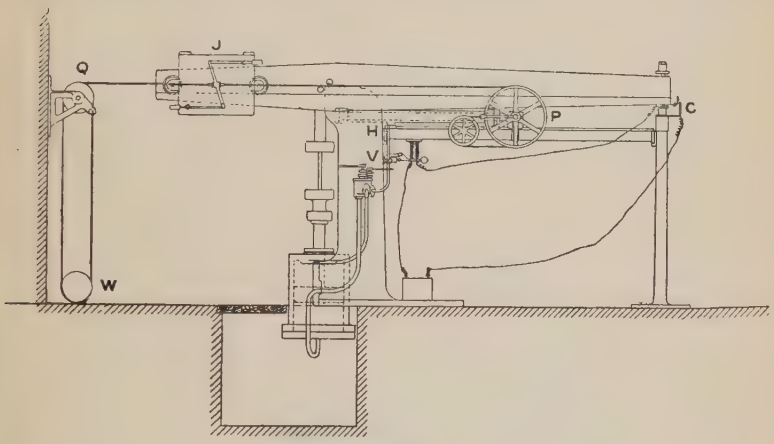


FIG. 78.

to the right, and the two handles to the belt-gear r_1, r_2 and the hand-wheel h are within reach without moving.

91. *Hydraulic Power for Moving the Jockey-weight and Automatic Adjustment of the Jockey-weight.*—In 1891 Mr. Wicksteed patented an arrangement for moving the jockey-weight in his single-lever testing-machines by hydraulic power. The advantage of this is that the speed at which tests can be carried out is increased up to thirty or more tests per hour. In steelworks where a very large number of tests have to be made this may be necessary, though it has some counterbalancing disadvantages. In connection with this an automatic regulation of the jockey-weight was also patented. In the automatic arrangement, whenever the lever lifts, it opens a valve admitting pressure water to the

hydraulic cylinder driving the jockey-weight, and the jockey-weight travels forward. If the lever falls the valve closes and the travel of the jockey-weight is arrested.

In fig. 78, H is the hydraulic ram which moves the jockey-weight. The ram acts on a crosshead carrying a pair of pulleys P, one on each side of the testing-machine lever. A pair of wire cords passing over these pulleys are attached to the jockey-weight J. These are kept tight by other wire cords passing over pulleys at Q and carrying a counterbalance-weight W. The counterbalance draws back the jockey-weight when the pressure in H is released. The wire cords are attached to the centre of two links carried by radius rods attached to the jockey-weight J. The points of attachment to the link move in vertical lines, the linkwork being in fact a Watt parallel motion. Hence, any vertical motion of the jockey-weight does not strain or deflect the cords. The wire cord is self-supported between its pulleys, and cannot produce any vertical strain on the jockey-weight. The parallel motion on the other hand is wholly carried by the jockey-weight, and forms part of it.

For automatic regulation of the position of the jockey-weight there is a valve at V controlled electrically by contacts at C. When contact is made by the rising of the lever the valve lifts. If the lever falls contact is broken and the valve closes.

Mr. Wicksteed states that the hydraulic arrangement has been largely used, but that the automatic regulation has not at present been adopted, partly because in steelworks where inspectors of the Board of Trade superintend much of the testing, it is preferred that the lever should freely swing through a considerable range, so that there may be no doubt as to whether the lever is balancing the tension on the test bar or resting on its stop. If automatic regulation is adopted, it is essential that the lever should have a very small range of motion, or there will be an action analogous to the 'hunting' of a governor.

92. *Wicksteed's Spring-balanced Testing-machine with Autographic Recorder.*—It is difficult with lever testing-machines to keep the lever floating during the yielding and during the drawing down of a test bar. Hence at those periods an autographic record is liable to be faulty. Fig. 79 shows a machine designed by Mr. Wicksteed which overcomes this difficulty. The jockey-weight *a* is run out to

the end of its travel and then brought into the floating condition by the spring *s*. If now the specimen is strained by worm-wheel and screw *w*, the load on the spring diminishes

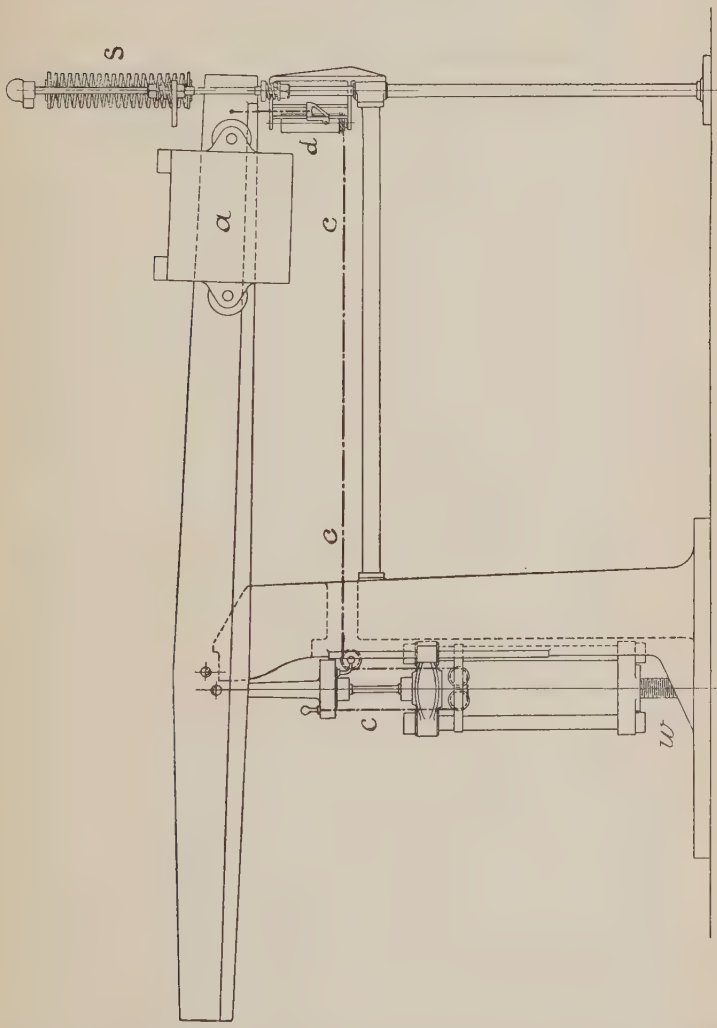


Fig. 79.

by the amount of the stress on the specimen and the lever rises in exact proportion to the load carried by the specimen. A fine chain *c c c* attached to the shackles and passing under the axis of the test bar rotates a recording drum *d*

proportionally to the elongation of the test bar, and a pencil sliding vertically is connected to the lever and moves proportionally to the load on the test bar. The observer has merely to strain the test bar and automatically the pencil records at each moment the load and elongation. The lever remains in stable equilibrium throughout the test, if conducted with reasonable care.

It is noticed that if straining is stopped at or beyond the yield point, the lever falls a little for about a minute, indicating a decrease of the resistance of the test bar.

93. *50-ton Single-lever Machine of the Société Alsacienne of Grafenstaden, Mulhouse.* — A larger compound-lever machine made by this firm was described in *Engineering*, June 25, 1880. The neatly arranged machine shown in Plate III., fig. 2, is a single-lever machine of the type shown in fig. 71. The specimen is held between the shackles A_1, A_2. The upper shackle is connected to the straining mechanism, which in this case is a screw having on it a long nut, driven by gearing G. The screw is prevented from rotating by a slide. The lower shackle is attached to the main lever F at a knife-edge. This lever is connected by links to the subsidiary beam F_1, which carries the fulcrum knife-edge. The links have knife-edges at the points at which they rest on F and F_1. A jockey-weight runs on the graduated lever F. The lever F_2 carries a counterweight to put the main lever in balance.

COMPOUND-LEVER MACHINES

94. *100-ton Testing-machine of Messrs. Adamson & Co., of Hyde, near Manchester.*—The machine shown in fig. 80 is a compound-lever horizontal machine. This machine is specially designed for use in large iron and steel works, where specimens are required to be tested for commercial purposes, rather than for very accurate scientific work. The machine, with all its appliances, is entirely self-contained; it is mounted on a heavy cast-iron foundation, which requires no holding down. It is capable of testing materials in tension, compression, and bending; by a special arrangement it may also be used for torsion. The testing stress is obtained by a hydraulic cylinder and ram 6¼ inches in diameter. The cylinder is of forged steel, and is intended to carry a working pressure of about three tons per square inch. The pressure

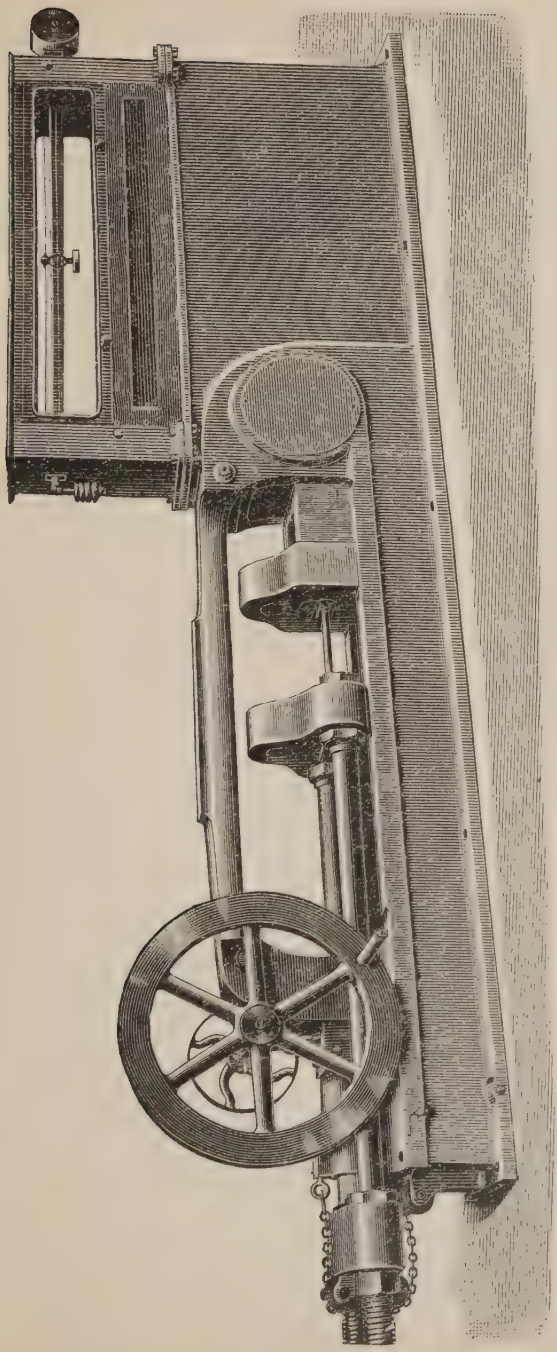


Fig. 80.

is obtained by a small double-cylinder pump, driven by cranks, and provided with a flywheel, pulleys, and handle for hand or power driving. The plungers are made on the compound principle, one small one working inside an annular plunger. When it is required to pump rapidly at low pressures, both of them are coupled together, forming one large plunger; but for high pressures the inner one only is used; then the speed has to be sacrificed for pressure. This arrangement permits two men to pump up to the full power of the machine. The pressure on the ram is transmitted to a substantial cast-steel crosshead by means of two steel ties, 3 inches in diameter, running along either side of the machine. These ties are screwed at the ends to allow of the crosshead being adjusted for various lengths of specimens.

95. *Olsen Compound-lever* 100-*ton Testing-machine* (Plate III., fig. 1).—This is of the type largely adopted in America, the mechanism being in principle the same as that of a platform weighing-machine. Four columns on the platform E carry the steel plate B, to which one end of the specimen is attached. Four straining-screws carry the plate C, to which the other end of the specimen is attached. The columns supporting B rest on the lever system F, F. The straining-screws carry the large driving-nuts H, which are put into action by the gearing below the levers. The nuts abut against the frame through roller bearings, to diminish friction.

The platform E rests on three main levers, acting as a single lever. Beyond the platform the three levers act through a stirrup on the second lever F_2, and this again is connected with the third lever or graduated steelyard F_3. A small poise or jockey-weight gives the measurement of stresses from 0 to 5,000 lbs.; a larger poise, stresses from 5,000 to 100,000 lbs.; and an additional weight on the end of the lever adds 100,000 lbs. The screws and driving-nuts take the place of the hydraulic press used in other machines. A crossed belt on the pulley T, and an open belt on the pulley U, drive the gearing. A friction-clutch engages either pulley with the driving-shaft. There is also a slow motion by friction-gear V.

96. *Horizontal Testing-machine of Messrs. Buckton & Co.*—Several machines of a horizontal type have been constructed by Messrs. Buckton & Co., the arrangement being to some extent based on that of the Werder machine, but the small fulcrum

distance of the simple lever Werder machine is rendered unnecessary by the adoption of a multiple-lever arrangement. One of these machines has been erected at University College, Cardiff, under the direction of Professor Elliott.[1] The machine is capable of testing to 100 tons. Fig. 81 shows the arrangement; A is a bed-plate running the whole length of the machine. It carries the hydraulic straining-press at B, the ram being 12 inches diameter and 24 inches stroke. Fixed to the ram head is the heavy casting, or sliding frame C, C, about 18 feet long, sliding in groves in the bed A. The crosshead D can be traversed between the top and bottom of the sliding frame, and at any desired point locked to it by a double key and nuts. Through the sliding frame and crosshead the straining action due to the pressure on the ram B is

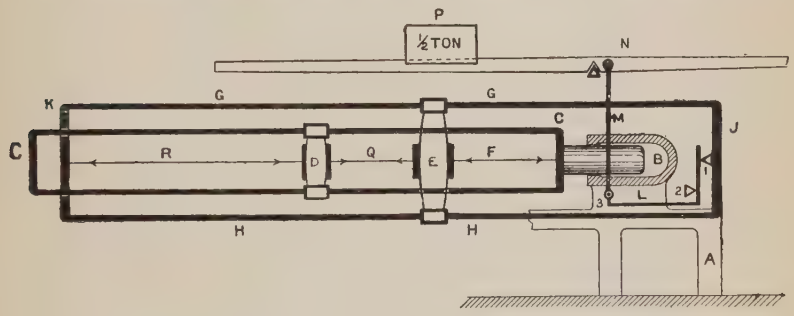


FIG. 81.

applied to the specimen. The stress-measuring apparatus is applied to the second crosshead E. This crosshead is attached to two steel rods G and H, 3½ inches in diameter, and 24 feet long, terminating in the crossheads J and K. Any thrust applied by a test bar to E produces tensions in G and H, which are transmitted to J. At J the stress is balanced by the lever measuring system. There is a heavy bell-crank lever L, with knife-edges at 1, 2, and 3, and a second horizontal lever N connected to the first by the link M. The stress is balanced by a movable jockey-weight P. A scale on the lever indicates the amount of stress on the specimen balanced.

If a specimen is placed at F the straining action is a thrust; if placed at Q in suitable shackles attached to D and E, a tension; if placed at R the straining action is a thrust

[1] *Journal of Junior Institution of Engineers*, 1898.

and the specimen is in compression. By setting the crosshead D in different positions along the sliding frame any tension or compression specimen can be taken in the machine up to 10 feet in length. The crosshead E carries a bending beam for testing beams up to a span of 10 feet.

The sliding frame C rests on the fixed bed, and its friction does not affect the measurement of the stress. The tension rod frame G K H J is in a different condition. Any friction arising in the small motion of this frame would be measured as part of the stress. Hence, it is supported from the floor by two double knife-edge supports and by a third support forming a double adjustable knife-edge sling. The crosshead K carries a heavy horizontal bending beam for spans from a few inches up to 10 feet. The distance between the knife-edges 1 and 2 is 4 inches. The horizontal distance 23 is 32 inches. The ½-ton poise P reads from 0 to 100 tons with a travel of 200 inches or moves 2 inches to the ton. A subsidiary pair of knife-edges 1 and 2 at 8 inches apart can be brought into action and then P measures to 50 tons, travelling 4 inches per ton. The machine is provided with a torsion apparatus capable of applying a torque of 100 inch-tons.

The hydraulic straining-press is worked by an accumulator, fed by a single-throw differential pump driven from a shaft, which in turn is rotated by an electromotor. The diameter of ram of the accumulator is 6 inches, and the stroke 9 feet; the maximum pressure is about 2,000 lbs. per sq. in. Professor Elliott claims for this machine great facility for adaptation to different kinds of work, so that changes can be made from one kind of testing to another in four or five minutes.

Messrs. Buckton & Co. have since constructed a machine of a similar type, of a capacity of 300 tons, for the Conservatoire Nationale des Arts et Metiers, Paris (*Engineering*, September 1904). This machine will test a strut 88 feet long and 3 feet square, or a cable thirteen fathoms long of iron 4½ inches diameter. It will test a beam 3 feet broad by 6 feet 8 inches deep by 20 feet between supports. The machine is arranged for tension, compression, bending, torsion, shearing, and punching. The accuracy of the machine has been tested by means of calibrated copper crushing cylinders.

A somewhat similar horizontal 300-ton testing machine

has been constructed by Messrs. W. & T. Avery [1] for the University of Birmingham. It will take tension specimens of 33 feet length, columns of 30 feet length and beams of 20 feet span.

97. *Horizontal 500-ton machine at Gross-Lichterfelde.*—This machine was built by Hoppe of Berlin. It will take tension test bars 56 feet in length and compression bars 49 feet in length. It has at one end a movable hydraulic press, so arranged that the cylinder can be locked to the bed, the ram moving forward, or the ram can be locked so that the cylinder moves backward. The straining cylinder can therefore be placed at any point in the length of the bed and can exert either a thrust or a pull. The weighing apparatus is at the other end of the bed.

98. *600-ton Testing-machine of the Union Bridge Company at Athens, Pa.*—This machine was constructed with the object primarily of testing the full-size

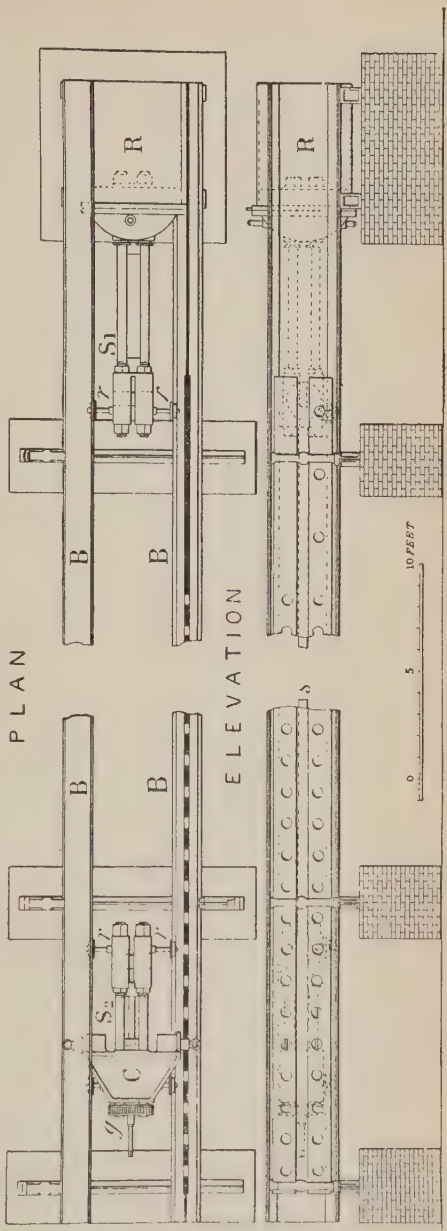


FIG. 82.

[1] *The Engineer*, May 21, 1909.

eyebars which are so largely used in American bridge construction.

Two horizontal riveted girders B, B (fig. 82), 60 feet in length, supported by cross-girders on five masonry piers, form the frame of the machine. At one end of the frame is a large hydraulic press cylinder R, with a freely moving piston. This has four piston-rods, to which is attached a crosshead carrying shackles S_1 for one end of the test bar. There is a movable tail-piece C, which can be attached at any point in the length of the frame, which carries a similar crosshead and shackle S_2 for the other end of the test bar. The crossheads are carried on accurate wheels *r*, *r*, running on a flange of the frame track fixed to the lower girders. The tail-piece having been fixed to the girders at a suitable distance from the hydraulic press, the specimen is introduced. Then pressure is applied to the piston of the press, and increased till the specimen breaks. The pressure on the piston is measured by a Shaw mercury column and by a spring pressure-gauge. The load on the specimen is taken to be equal to the pressure on the press cylinder. It will be seen that in this very large and important machine the principle of construction is simple, the lever weighing apparatus being dispensed with.

The hydraulic press cylinder R is of cast steel, 4 feet $3\frac{3}{4}$ inches bore and 6 feet $0\frac{1}{2}$ inch long. It has an area of 2,039 inches, and an effective stroke of 4 feet 11 inches. The maximum water-pressure for which provision has been made is 600 lbs. per square inch. The cylinder is secured to the girders by bolts, and its back end is left open, so that the piston can be seen.

The main girders B, B are of wrought iron, 60 feet long, 3 feet 6 inches high, built of plates and angle bars, rolled in one length. Holes, $6\frac{1}{2}$ inches diameter and 18 inches apart, are bored through the web for the bolts of the tail-block. Along this part of the web it is $2\frac{1}{2}$ inches thick.

The tail-block C is a steel casting, which may be attached to the main girders by two pins each side, fitting the $6\frac{1}{2}$-inch holes. Geared steel nuts *g* give a further adjustment of the distance of the shackle from the tail-block.

To provide for recoil between the shackle and tail-block there is a rod attached to the shackle passing through a friction-clamp on the tail-block. The eyebars are attached to the shackles by a $7\frac{1}{2}$-inch pin in an elongated hole $7\frac{1}{2} \times 9$

in the shackle. This permits the specimen to recoil independently of the shackle. When smaller pins must be used collars reduce the size of the pin-hole.

The shackle attached to the hydraulic press piston is similar. The piston has a gland and hemp packing, and the piston-rods also pass through stuffing boxes. The piston-gland is tightened till the leakage, with maximum pressure, is reduced to a thin film of water discharging uniformly round the piston. After a specimen is broken a discharge-cock is opened to a tank 4 feet 6 inches below the cylinder. The small vacuum thus formed, equivalent to 1½ lb. per square inch on the piston, is found sufficient to move it home. Hence it has been assumed that 3,000 lbs. represents the maximum allowance to be made for the friction of the hydraulic press. For practical purposes this allowance is disregarded.

The pressure is obtained by a pump with three single-acting plungers, 2¼ inches in diameter and 10 inches stroke, working at slow speed. An engine with two cylinders, 8 inches diameter and 8 inches stroke, works the pumps.

With a maximum load the stresses on the parts of the machine are as follows:

Main girders . . .	7,100 lbs. per sq. in.	compression
Steel castings . . .	15,000	„	„
„ . . .	13,000	„	„ tension
Connecting rods . .	15,000	„	„
Bolts	12,000	„	„ shear

All these stresses are for the net effective sections, and the margin of safety appears to have proved sufficient under the shock of sudden release of load. Bars varying from 5 to 18 square inches section have been broken in the machine.

The machine was designed by Mr. Charles Kellogg. The idea involved in its design is thus stated by Mr. Macdonald: 'It is not contended that this is an instrument of precision, or that in sensitiveness or accuracy it is the equal of the testing-machine at Watertown Arsenal. Mr. Kellogg would be the last person to invite comparison in that respect with the superb invention of Mr. A. Emery. What he has accomplished has been the construction of a machine at moderate cost which will test to destruction full-sized sections as they are required for structural purposes, with rapidity and reasonable accuracy.'

The particulars and description of this machine have been taken from a paper read before the American Society

of Civil Engineers by Mr. Charles Macdonald, M.Am.Soc.C.E.[1] A similar machine of 1,200 tons capacity has been constructed by the Phœnix Iron Company of Pennsylvania.

99. *Whitworth Hydraulic Testing-machine.*—An hydraulic machine which has been extensively used in this country is made by Whitworth. A description of a 50-ton machine of this kind in use at the Midland Works, Derby, is given in a paper by Mr. Peet.[2] The ram of the hydraulic cylinder is 50 square inches area and 6 inches stroke, with a cup leather packing, working with a maximum pressure of one ton per square inch. The machine is driven by a set of belt-driven three-throw pumps, which force the oil through an accumulator and are thrown out of gear automatically before testing. The rate of straining is then regulated by a screw-down valve. The pressure in the hydraulic cylinder is measured by two Schaeffer & Budenberg pressure-gauges, one graduated to 100 and the other to 10 tons. Subsidiary apparatus is required (1) for testing the accuracy of the pressure-gauges, (2) for determining the friction of the testing-machine. To test the pressure-gauges, weights resting on a frictionless ram of $\frac{1}{10}$th square inch area are used. Each weight balances 224 lbs. or $\frac{1}{10}$th of the maximum load on the ram of the instrument. The weights are revolved when readings are taken to annul friction. The friction of the machine is partly due to friction of the sliding pieces, but chiefly to the cup leather. To determine this a ram cylinder, precisely like the machine cylinder, is coupled to the latter, and the ram in one cylinder is used to drive the ram in the other, a small leak through a cock being allowed to secure motion. Half the difference of pressure in the two cylinders measures the friction due to one cup leather. The friction is 112 lbs. with no load on the ram, rises to 448 lbs. with a pressure of 0·7 ton per square inch on the ram and decreases a little with higher pressures.

MANOMETER MACHINES

100. *The Thomasset Machine*[3] (fig. 70).—M. H. Thomasset, of Paris, constructed, apparently about 1872, a machine differing in its mode of action from previous machines in two ways. (1) To force the water into the hydraulic press ‘ a quiet

[1] *The Railroad and Engineering Journal*, vol. lxi. p. 71.
[2] *Proc. Inst. Mech. Eng.*, 1898.
[3] Lebasteur, *Les Métaux*, p. 52.

compressor' ('compresseur sterhydraulique'), like that used in oil presses, is employed instead of pumps. It has the advantage of convenience, and of preventing the pulsatory action produced by pumps. However, it requires more power to drive it. (2) In the weighing apparatus the pressure of a liquid column acting on a large diaphragm, which forms a virtually frictionless piston, is employed to balance the stress on the specimen. This has the advantage of convenience, cumbrous weights being dispensed with. It has the further very important advantages that the inertia of the weighing apparatus becomes very small, and the load adjusts itself perfectly automatically to the stress. The slightest variations of stress are indicated by the rise of the liquid column, which balances the stress independently of any manipulation by the operator. Apart from the question of the success of M. Thomasset in overcoming the difficulties of a new problem, his machine has very great merit from a theoretical point of view.

One shackle of the machine being attached to the ram of a press, the other is attached to the short arm of a knee lever. The longer arm presses on the centre of a diaphragm covering a circular cistern of mercury, or of water communicating with the cistern of a mercury manometer. The diaphragm is a vulcanised-rubber sheet fixed round its edge by a ring, and receiving the load from the lever on a loose circular metal plate only slightly less in diameter than the cistern.

Let Ω be the area of the circular diaphragm in sq. centimetres; P the stress on the specimen in kilograms; n the leverage of the bent lever. The total pressure on the diaphragm is P/n kilograms, and the pressure in the cistern is $P/\Omega\, n$ kilograms per sq. cm. But if h is the height in cm. of the mercury column in the manometer, measured from the level of the cistern (or, strictly, from the point where the mercury stands with no stress on the specimen),

$$\frac{h}{76} = \frac{P}{\Omega\, n}.$$

If $\Omega = 5{,}000$ sq. cm. (about 2·6 feet) in diameter; $n = 5$; then a column of mercury $1\frac{1}{2}$ metre (5 feet) high will balance 50,000 kilograms (50 tons) of stress. As the section of the mercury column is only $\frac{1}{3000}$ of the area of the diaphragm, the whole movement of the diaphragm for a load of 50 tons is only half a millimetre (0·02 inch).

101. *The Maillard Testing-machine* (fig. 73).—A machine[1] based on the same principle as the Thomasset machine was designed by Colonel Maillard for use in the French arsenals. Broadly speaking, it is a Thomasset machine in which the lever is got rid of, and the pull taken directly on the diaphragm. This involves an enlargement of the size of the diaphragm, and some other changes. The machine as hitherto constructed is only suitable for short specimens, and is only arranged for tension.

In this machine the specimen is held horizontally between shackles, one attached to the ram of a hydraulic press, the other to a cross which pulls on a diaphragm in a cistern containing fluid. This short cylindrical cistern has the same axis as the hydraulic press, and necessarily the diaphragm which receives the pressure is on the side furthest from the test bar, so that the crosshead is forked to surround the cistern. The diaphragm is of caoutchouc, protected by a metal plate. The cistern communicates by a pipe with a Galy-Cazalet manometer, or a mercury manometer. The cistern is carried on trunnions upon a carriage sliding horizontally. By means of a screw and hand-wheel the position of this carriage can be adjusted to suit different lengths of specimen.

The stress in the test bar, transmitted through the shackle and crosshead to the plate or piston at the back of the cistern, is exactly balanced by the fluid pressure. The diaphragm moves at most only a small fraction of a millimetre, so that the friction and bending resistance of the diaphragm is quite negligible. Consequently, if the graduation of the manometer is correct, the stress is determined with great accuracy. If P is the stress on the bar, h the rise of the mercury column in the manometer above the zero at which it stands when no stress is applied, δ the density of the mercury, s the area of the diaphragm, s_1 and s_2 the large and small areas of the manometric piston,

$$P = h \delta s \frac{s_1}{s_2}.$$

To eliminate errors due to uncertainty as to the areas of the diaphragms, to capillarity, and so on, the manometer is graduated by experiment. The cistern is removed from

[1] Lebasteur, p. 53.

the machine, laid horizontally, and loaded with standard weights.

In a good manometer the tube must be at least 3 centimetres in diameter ($1\frac{1}{4}$ inch); with a smaller column, drops of mercury remain attached to the tube when the column falls. The manometric piston in the manometer used is so arranged that a centimetre rise of column corresponds to the kilogram per square centimetre on the smaller piston, and consequently on the diaphragm of the main cistern of the testing-machine. Hence, if n is the rise of column in centimetres, and s the area of diaphragm in centimetres—

$$P = n\,S.$$

In the machine at the Ruelle Foundry the diameter of the large diaphragm is 9 feet.

Dr. Nicholson has constructed for the Municipal Technical School at Manchester a 750-ton compression machine. The machine is a hydraulic cotton press modified for the purpose and fitted with autographic recording and regulating devices. The load acts on a copper diaphragm 3 feet in diameter. The pressure in the fluid supporting the diaphragm is measured by a mercury column 105 feet in height.

102. *Wire-testing Machine of Messrs. W. H. Bailey & Co., of Salford.*—Fig. 83 shows a very nicely arranged small-tension machine, on the same principle as Col. Maillard's. One end of the specimen is held in friction-grips in a shackle attached to a screw and hand-wheel, which takes up the elongation. The other shackle is attached to crossheads and links, which surround the diaphragm chamber, and apply the load on the back of the diaphragm. The pressure in the diaphragm chamber is transmitted to a pressure-gauge and to a mercury column, either of which can be used. There is a valve on the pipe, allowing flow towards the pressure-gauge or mercury column, but preventing back flow. This holds the gauge at the maximum pressure, and prevents injury when the specimen breaks and the load is suddenly removed. A small hand-wheel opens this valve and lets off the pressure slowly. The machine will give a tension of 4,500 lbs.

Some years since the author modified this machine so as to adapt it as a convenient student's machine for tests of various kinds. The modified machine is shown in fig. 84. By the addition of a crosshead for transverse tests it becomes a convenient machine for bending-tests of cast-iron bars

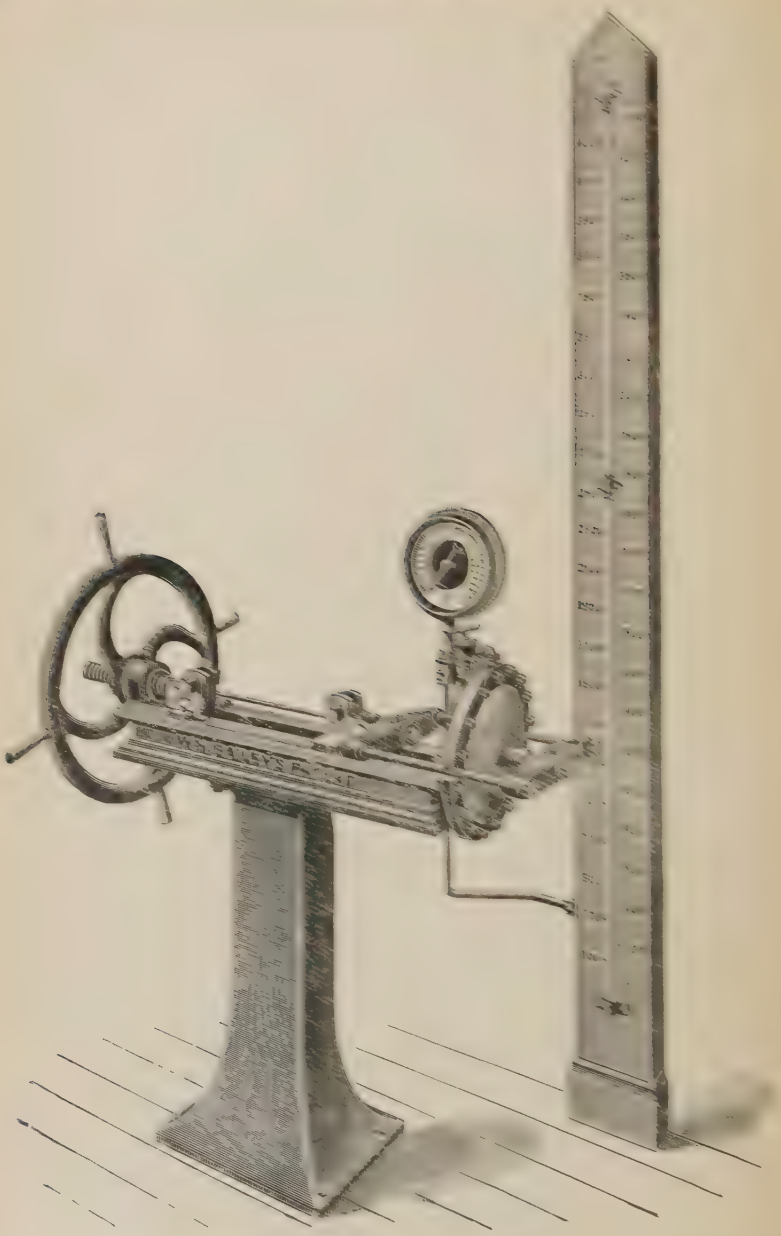
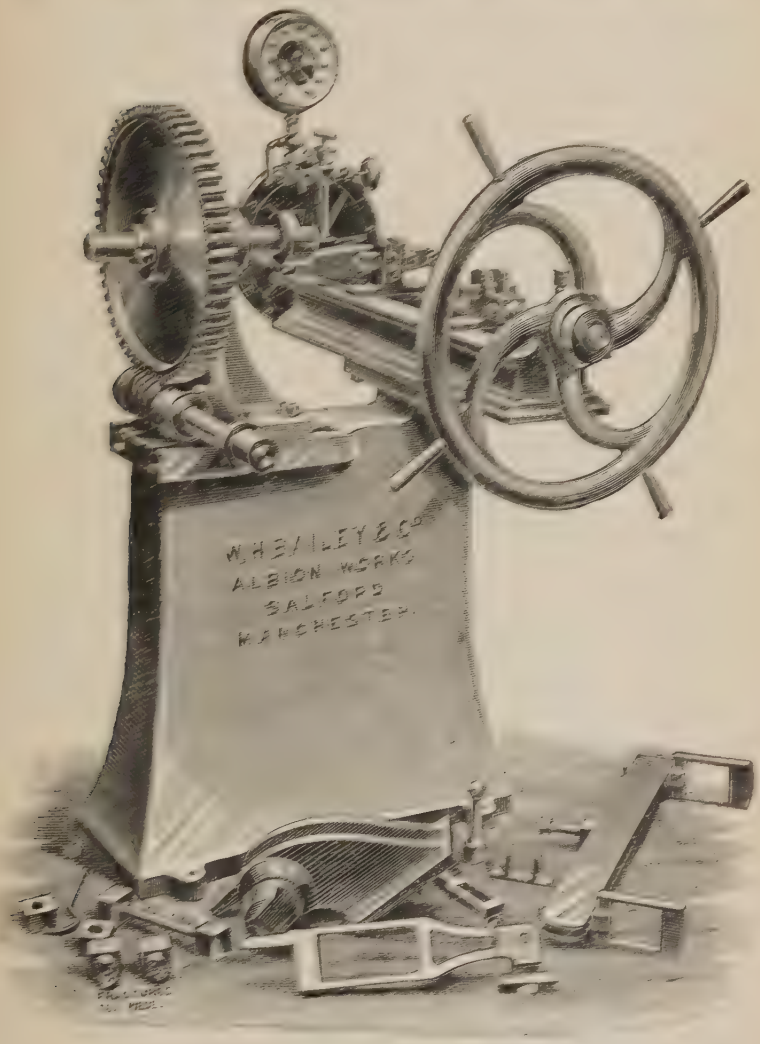


FIG. 86.

or for tests of wood and similar materials. The addition of a torsion arrangement makes it an excellent machine



for torsion tests even of wrought iron or steel. The torsion bar is gripped at one end by a rotating head connected with a worm and worm-wheel driven by hand. At the other

end a lever carried by ball bearings, so as to be nearly frictionless, even with high loads, carries one end of the torsion specimen, and transmits torque exerted by the worm and wheel to be measured by the fluid pressure arrangement.

EMERY MACHINES

103. *The 450-ton Emery Testing-machine at Watertown Arsenal, U.S.A.*[1]—In 1872 a committee of American engineers was formed to urge on the Government of the United States the importance of a thorough and complete series of tests of American iron and steel. Subsequently, by direction of the Government, a Board was constituted for the purpose of carrying out tests of iron, steel, and other metals, and an appropriation was made for the construction of the necessary apparatus. In 1875 a contract was made with Mr. A. H. Emery for the construction of a machine capable of exerting a stress of 800,000 lbs., and testing specimens in tension up to 28 feet in length and 30 inches in width, and in compression columns up to 30 feet long. In 1879 the machine was completed satisfactorily, and it is one of the largest and most accurate testing-machines in the world.

Before acceptance by the Board, a link of hard iron, 5 inches in diameter, was placed in the machine, and slowly strained in tension till it broke at 722,000 lbs. Without any readjustment, a horse-hair was then fixed in the machine, and broken at an indicated stress of 1 lb.

To give an idea of the sensitiveness of the weighing apparatus of the Watertown machine, it may be compared with a delicate chemist's balance. A good assay balance will carry 1 gram, and turn with $\frac{1}{10}$ of a milligram, or $\frac{1}{10000}$ of the load. A fine balance exhibited at Philadelphia, with 1 lb. in each scale, would turn with $\frac{1}{5000000}$ of its load. Ordinary fine balances weighing to 1 lb. will turn with 1 gram, or $\frac{1}{700}$ of the load. Now, before the Emery machine was completed it was arranged as a balance. In seven weighings of a load of 100 lbs. the greatest difference in the observed weights was $\frac{1}{1750000}$ of the load. In nine weighings of 200

[1] See also a 'Description of Emery's Testing-machine,' by H. R. Towne, *Proc. Inst. Mech. Eng.*, 1888, p. 206 and p. 448; also 'Emerysche Materialprüfungsmaschinen, construirt von Sellers & Co.' (Martens), *Zeitschrift des Vereines Deutscher Ingenieure*, Band xxxix. 1895.

lbs. the difference between the greatest and least observed weight was only $\frac{1}{2850000}$ of the load.

Since the construction of the Watertown testing-machine smaller machines of the same kind have been made by the Yale and Towne Manufacturing Company of Stamford, U.S.A.[1] In no other machine is the stress exerted in such a purely static manner. It is almost impossible for any shock or inertia stress to be exerted on the specimen. It may seem that the delicacy of the machine must be such as to unfit it for ordinary rough commercial testing. On this point the author cannot speak from personal experience, but, so far as he can judge, this is not the case.

The Emery machines differ essentially in principle from any others. They are really compound-lever machines, with a hydraulic press acting on one end of the specimen, and a lever-weighing apparatus on the other end. But their greatest peculiarity is that a kind of hydraulic lever is introduced between the specimen and the weighing apparatus. The pull of the specimen is taken on a diaphragm or 'hydraulic support,' the action of which is like that of the diaphragm in the Maillard machine. The fluid pressure in the hydraulic support, which is exactly proportional to the stress on the test bar, is transmitted through a very small pipe to act on a frictionless diaphragm of comparatively small size, and it is the pressure on this second diaphragm only which has to be balanced by the lever-weighing apparatus. The weighing apparatus can therefore be made of small size, and of the utmost refinement and accuracy.

In the 75-ton machine the ratio of areas of the diaphragms is 20 : 1, so that the lever-weighing apparatus has to balance 3·75 tons only with the full load. There are three levers with ratios of 1 : 20, 1 : 20, and 1 : 40, so that the resultant leverage is 320,000 to 1.

The action of the Emery machine may, perhaps, be made clear by the diagrammatic sketch of a vertical machine (fig. 85). A tension specimen is shown between the shackles s_1 s_2. The upper shackle is held by the ram of the hydraulic press, which can be adjusted on the guide-screws G, G. These screws are fixed on the frame F, F of the machine. The lower shackle is attached to a yoke or frame Y, Y, which transmits the load to the hydraulic support. At s is a thin

[1] The Emery machine is now manufactured by Messrs. Sellers & Co., of Philadelphia, U.S.A., and they have introduced many improvements of detail.

circular brass sac, filled with alcohol and glycerine, supported over all its area, except a ring $\frac{1}{8}$ inch wide at its circumference, by the strong and rigid crossheads P_1 P_2. When the machine is acting, as shown, in tension, the yoke transmits the load to the crosshead P_2, and thence through the sac s to P_1, which rests against the stops a, a on the frame. For compression the yoke presses downwards on P_1, through s to P_2, and P_2 then rests on the stops b, b. The whole play of the crossheads between the stops a and b is only $\frac{1}{5000}$ inch.

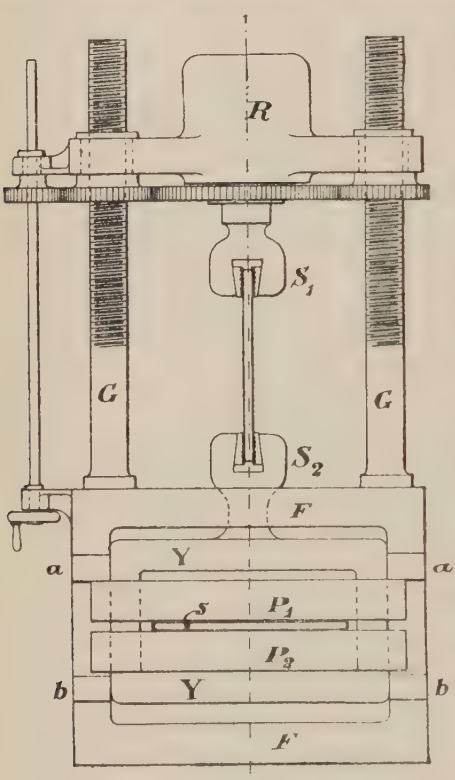


Fig. 85

The movement of the yoke and compression of the hydraulic support is determined by the amount of motion permitted in the lever-weighing apparatus. With the 75-ton machine, when the indicating lever moves 4 inches (2 inches above or below mean position) the greatest compression of the sac s is only $\frac{1}{80000}$ inch. The movement of the smaller diaphragm and of the fulcrum of the first lever is $\frac{1}{40000}$ inch; the free end of the first lever moves $\frac{1}{2000}$ inch, and that of the second lever $\frac{1}{10}$ inch. It is on the smallness of the movement that the exactitude of the action of the hydraulic support depends.

It is a peculiarity of the lever-weighing system that knife-edges are replaced by an arrangement more sensitive and exact, and less liable to injury by wear. In place of the knife-edge Mr. Emery uses a thin flat blade of steel rigidly fixed in the lever and its support. If the lever

moves, this bends. But the resistance becomes insensibly small if the motion of the lever is small and the blade of steel thin. Fig. 86 shows two arrangements of these substitutes for knife-edges. In *a* the steel blades are in tension; in *b* they are in compression. The steel is 0·004 to 0·06 inch thick, and the blades are so wide that the stress in the steel does not exceed 18 to 30 tons per sq. inch. The blades are fixed by forcing them into grooves by hydraulic pressure, about three times as great as the working load.

A somewhat similar arrangement is adopted to get rid of all sliding friction in the moving parts of the testing-machine (fig. 85). The yoke and crossheads do not slide in the frame, but are free. They are guided without friction, and for a

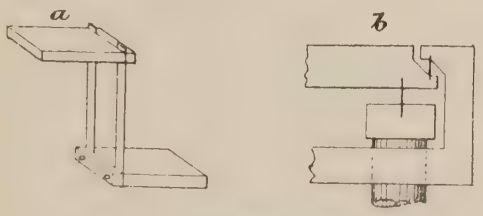


Fig. 86.

minute amount of motion without sensible resistance, by four flat flexible plates attached to each piece and to the frame.

Plate IV. gives a general view and Plate V. a plan and elevations of the Watertown Emery machine. The bed of the machine consists of a long track, built in sections set on masonry. At the right hand is the hydraulic press 1569 (fig. 1), with its shackle or holder 1475. At the left is the hydraulic support, the crossheads of which are seen at 1455, 1456, with the other shackle 1475. The frame at the left end is connected with the press by the guide-screws 1450. The hydraulic press is carried on a four-wheel truck, and can be set at any distance from the hydraulic support to suit different lengths of test bar. The guide-screws are 48 feet long and 8¼ inches diameter, and are driven by the geared nuts 1569 and the gearing at the extreme right of the figure. When the gearing is not acting the press is locked to the screws. The press has a 20-inch ram, with a piston-rod 10 inches diameter. The press is worked by accumulators, and acts in both directions, according as tension or compression is required.

In each of the test-bar holders there are two 14-inch hydraulic presses which grip the specimen with a force of 500 tons. The space for the ends of the specimen is 10 inches deep in the middle and 5 inches at the sides, and it is 30 inches wide.

The hydraulic support rests on a longitudinal slide, its motion being controlled by powerful buffer-springs, which absorb the recoil when the specimen breaks. In ordinary conditions the buffer-springs merely hold the hydraulic support in its middle position. When a specimen breaks, the press and hydraulic support recoil in opposite directions, the forces developed being opposed by the guide-screws. But as the recoiling forces are not exactly balanced, the

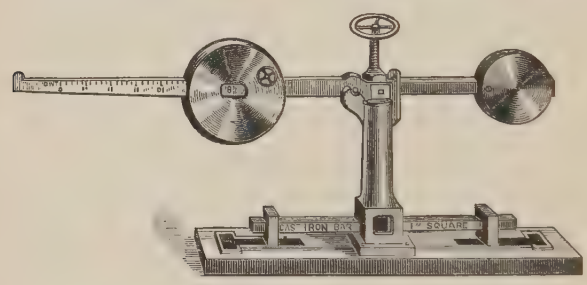


Fig. 87.

buffer-springs come into play and gradually bring the machine to rest. In tension, the pull is transmitted from the test-bar holder, through a great central link, to the back crosshead 1455, and so through the brass sack and front crosshead to the frame. In compression, the thrust comes first on the crosshead 1456.

The fluid pressure in the hydraulic support is transmitted through a small pipe to the pressure-gauges 1708, and also to the secondary diaphragm and the lever-weighing apparatus in the case 1705. In the general view (Plate V.) the hydraulic support is on the right, and the press and lever weighing apparatus on the left.

SPECIAL TESTING-MACHINES

104. *Torsional Testing-machines.* — In some testing-machines a special shackle is used for torsional stresses. But an ordinary large testing-machine is too clumsy for a

comparatively delicate test of this kind, and some of the shackles used in this way are defective in arrangement. For torsional tests a special small machine is desirable, and some such machines have been constructed recently.

A very neat little machine of this kind, by M. Thomasset, is figured in Lebasteur.[1] One end of the specimen is turned by worm-gear, while the other acts through a lever on a diaphragm and manometer. This seems to contain the essentials of a perfect torsion machine. A torsion arrangement used by the author is shown in fig. 84.

105. *Machines for Transverse or Cross-breaking Tests.*—Shackles for cross-breaking are provided with most large testing-machines, and will be described in the next chapter. For transverse tests of cast iron, small special testing-machines are useful. Bars of cast iron $3\frac{1}{2}$ feet $\times$ 2 inches $\times$ 1 inch, laid on supports 3 feet apart, with the deeper side vertical, break with from 20 to 40 cwts. placed at the centre, so that the loads to be dealt with in tests of this kind are not very great.

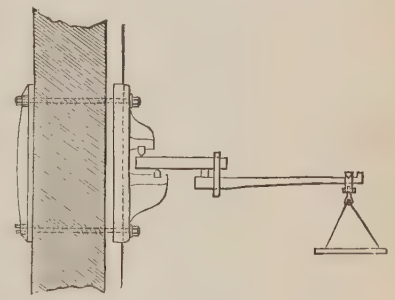


Fig. 88.

Fig. 87 shows a small machine for tests of this kind. The bar rests on knife-edges on the base-plate, and is loaded at the centre by a lever and jockey-weight.

Another convenient arrangement, known as the 'Balance Monge,' is in use in some gun factories. It consists of a bracket (fig. 88), fixed to a wall, having two opposed knife-edges. By a bridle and block a scale-platform is attached to the bar.

106. *Calibration of a Testing-machine.*—Experimental verification of the accuracy and sensitiveness of a testing machine is absolutely necessary, both in the first instance and at intervals afterwards. It will be sufficient to describe the process of verification adopted for the 100-ton Buckton testing-machine. The stress in this machine is weighed by a jockey-weight, and the first point to verify is that this jockey-weight is exactly 1 ton. The jockey-weight was adjusted at the

[1] *Les Métaux*, Lebasteur, Plate V.

Standards Office, and certified by the inspector. It is not difficult to verify this weight from time to time by lifting it, with one of the convenient steelyard weighing machines interposed between the crane-hook and weight.

Adjustment to Zero of Scale.—The adjustment is easily effected, and is necessary after any change of the shackles used. The jockey-weight is run back till the lever rests in absolute equilibrium midway between the stops. The vernier attached to the jockey-weight is then set to zero on the scale.

Verification of the Jockey-weight by the use of the Lever.—A very simple test of the accuracy of the jockey-weight is made in this way. A uniformly graduated scale runs along the lever. Division 5 coincides with the principal knife-edge on which the lever rests, and at division 45 a subsidiary knife-edge has been fixed. Bring the lever to balance, and set the vernier to zero. Then run back the jockey-weight to -1 on the scale. A weight of 56 lbs., hung at division 45, or forty divisions from the fulcrum, ought to be in balance with the jockey-weight moved one division back. If it is not, the jockey-weight is not a ton. This simple test, which can be made in ten minutes, is sufficient at any time to check the accuracy of the jockey-weight to about 12 lbs.

Verification of the Agreement of the Scale Divisions with the Short-arm Length of the Lever.—The fulcrum distance in this machine is 4 inches, and the unit of the scale must be 4 inches also. The agreement of the scale unit with the short-arm length is best determined by weighing. For this purpose a standard 1-ton weight, made of a suitable form, is hung from the shackle of the machine. The lever is balanced, and the vernier set to zero. The ton weight is then hung in the shackle, and balanced by the jockey-weight. The vernier ought then to read 1 ton on the scale. If it does not, the fulcrum distance must be altered, as it is inconvenient to alter the scale. Perhaps it is still more accurate to balance 56 lbs. at a leverage of 40 by the ton weight in the shackle without moving the jockey-weight.

Test of Sensitiveness.—In this machine the lever and jockey-weight, with the parts attached to them, weigh altogether about 5 tons, and this is therefore the minimum weight on the knife-edge. With this weight resting on the knife-edge there is a perceptible movement of the lever when 1 lb. is placed on the shackle, and a return if the weight

is removed. If the friction of the knife-edge is assumed to be proportional to the load, the error in 100 tons of stress would only be 20 lbs. Probably a greater sensitiveness than this could be obtained if necessary. The knife-edge of this machine is of the exceptionally great length of 22 inches. Any initial or induced flexure virtually broadens the knife-edge and reduces the sensitiveness. Hence a very long knife-edge, though more durable, is likely to be less sensitive than a shorter one.

Test of Neutrality of the Lever.—The centre of gravity of the lever and jockey-weight should be on the line passing through the knife-edges. If it is not so, the leverage alters, either decreasing or increasing as the inclination of the lever alters. The author has tested this directly by ascertaining the pull, with the lever in different positions, by a weighing-machine suspended in the shackles. The following tests were made by first placing weights on the shackle and taking them off; afterwards, by repeating the operation with weights on a small scale suspended from the long arm of the lever. Throughout the whole of these tests the lever was absolutely untouched, so that no vibration or swing was given to neutralise any friction in the machine. The weights placed on the shackle were, of course, at 4 inches from the fulcrum; the weights on the other side are reduced to equivalent weights, also at 4 inches from the fulcrum. The figures are the mean of the rise and fall in two series of tests taken at different times; the rise and fall in the two series of tests differed very little:

Weight on shackle in lbs.	Movement of end of lever in inches	Movement per lb.	Weight on long arm	Movement of end of lever in inches	Movement per lb.
1	·09	·09	1·4	·12	·08
2	·26	·13	2·9	·52	·18
3	·48	·16	5·7	1·21	·21
5	1·10	·22	8·6	1·98	·23
7	1·53	·22	11·5	2·49	·21

107. *Example of the Arrangement of a large Chain-testing Establishment.*—Under licence of the Board of Trade, certain establishments are appointed to test and certify chain cables, anchors, and other large structural pieces. As an example of such an establishment a short description may be given of Lloyd's Proving House, Netherton, near Dudley.

The testing-machinery consists of five testing-machines of 50, 105, 150, 200, and 300 tons capacity. The 50, 105, and 200 ton machines are used for proving chain cables of lengths up to 90 feet, and for testing anchors. The 150 and 300 ton machines are used for testing trial pieces and for experimental purposes. From each 15-fathom length of cable a trial piece of three links is cut out for testing, and if this is found satisfactory the whole length is subjected to a proof strain.

The 300-ton machine is adapted for applying either tensile, compressive, bulging, torsional, or transverse strain. Provision is made for the preparation of experimental samples, either by lathe or by shaping, slotting, or planing machine. There is also an apparatus for obtaining the limit of elasticity of metals. Chain cables up to $3\frac{1}{2}$ inches diameter have been tested and samples broken ; and anchors exceeding 10 tons, made in the district, have been tested here, a steam travelling-crane being used for lifting and moving the heavy articles.

The whole establishment is lighted by electricity ; four 1,000 candle-power arc lamps and a number of incandescent lamps are used for this purpose. The examination also of cables and chains after testing is done by the electric light during the winter months and in dull weather, so that the work can always be kept going. A 50 candle-power incandescent lamp is fixed on the front of each examiner's cap. For ascertaining the correctness of the centre lines of the different levers of the machines, a true plane surface-plate is used, 18 feet long by 8 feet wide, which is rather unique of its kind. About 250 tons of chains, cables, and anchors are tested here per week. The number of men employed is about 60.

CHAPTER VII

SHACKLES FOR HOLDING TEST BARS

108. The load required to fracture a bar varies with the mode of holding it in the testing shackles. The proper form of test bars to ensure comparable results in different tests will be discussed later. But the following general remarks may serve as an introduction to the examination of the methods of holding test bars in the machine.

Let ω be the section of a bar A (fig. 80), which breaks at $a\ b$ with a tension T normal to $a\ b$. Then if the direction of T passes through the centre of figure of $a\ b$, the stress is uniformly distributed, and T/ω is the real tenacity of the bar.

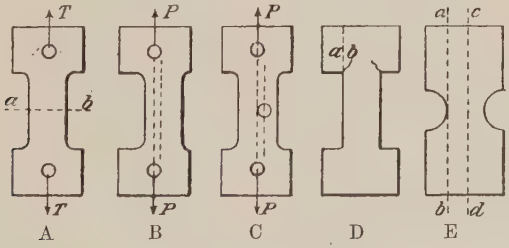


Fig. 89.

But, if these conditions are not satisfied, the stress is not uniformly distributed, and T/ω is the *apparent tenacity*, which may be less than the real tenacity to almost any extent.

(1) The stress on the cross-section will cease to be uniform if the resultant of the load P (fig. 89 B) does not pass through the centre of figure. The stress is then a varying stress, varying uniformly so long as the elastic limit is not passed, and according to some other law if it is passed. The specimen tears from the edge where the stress is greatest. At C, where the section $a\ b$ is modified by the presence of a drilled hole, the load is also eccentric, and this indicates how

non-uniformity of stress may be produced by unhomogeneousness of the material itself. A patch of material of different extensibility from the rest disturbs the uniformity of the stress in the same way as a hole.

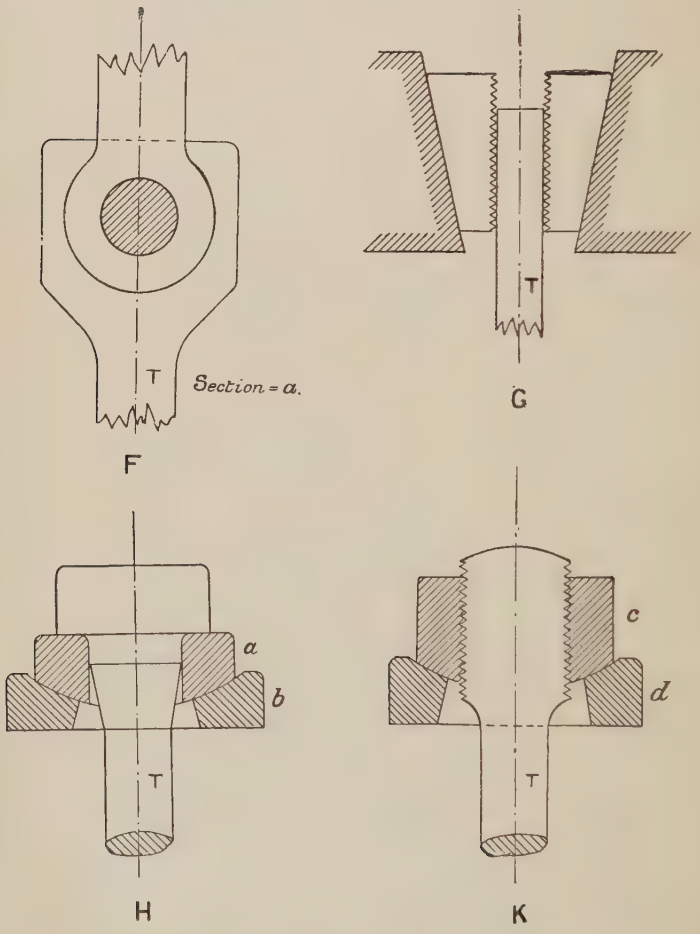


Fig. 90.

(2) The stress on cross-sections may be rendered non-uniform by the local action of contiguous material. Thus, bars of the form D are known to break with a low apparent tenacity. The unstrained material *a* prevents the elongation of the adjoining material *b*, and virtually renders the material unhomogeneous. In this case there is excessive stress at the

re-entrant corner, and fracture begins there. In the form E a similar action occurs ; but here the less strained material on either side of the section of fracture hinders local contraction, and may raise the apparent tenacity.

I. TENSION SHACKLES

The various methods of holding tension bars are shown in fig. 90. At F a bar with enlarged ends is held by a pin at each end. If the centres of the pins coincide with the axis of the bar, the condition of uniformity of stress on cross-sections is satisfied. At G the test bar T is held between two wedges with rough surfaces. This is the ordinary method of holding plate specimens. With ductile material it is fairly satisfactory, but it does not necessarily secure the condition that the resultant pull is in the axis of the bar. A more satisfactory arrangement to secure uniformity of stress on cross-sections is to support the test bar on collars or nuts having spherical surfaces, the centres of which lie in the line of pull of the testing-machine. H and K show arrangements of this kind for bars of circular section. At H the test bar T has a collar at each end, and this rests on a divided ring *a* having a spherical seating on a second undivided ring at *b*. At K the test bar has a screwed end, and a nut *c* on the bar, with a spherical surface, rests on a ring *d*. On account of the obliquity of the screw threads through which the pull has to be transmitted, this is not quite so satisfactory an arrangement as that shown at H. But, except for brittle materials, it is satisfactory in practice.

109. *Pin Grips.*—The oldest way of holding plate specimens in tension is to drill a hole for a pin at each end, and narrow the bar in the middle by milling, A (fig. 89). A hardened steel pin in the testing-machine shackles passes through each pinhole in the test bar. The pinholes must be accurately on the axis of the narrowed part of the bar to ensure uniformity of stress. But, besides this, it is important that the pins should be so large as not only to be safe against shearing, but so that the crushing pressure on the surface of the pinholes is not great enough to largely deform them. If this is not attended to the bar will break from the pinhole across the enlarged ends, even when these are considerably larger than the narrow part of the test bar.

Let *a* be the area of section of the bar at *a b*, and *d* the

diameter of the pin. Then the shearing section of the pin will be sufficient if

$$\tfrac{1}{2}\,\pi\, d^2 f_s = k f\ \ a,$$

where f_t and f_s are the tearing and shearing resistances of the plate and pin, and k a factor of safety not less than 3. If $f_s = f_t$,

$$d = 1{\cdot}38\,\sqrt{a}.$$

Thus, so far as shearing is considered, for breaking specimens of 4 sq. ins. area, a pin is required of $2\frac{3}{4}$ inches diameter.

Now let t = thickness of test bar, and f_c the pressure at which it crushes. Then, in order that the pinhole may be safe against deformation—

$$f_t\ a \text{ must be less than } f_c\ d\ t.$$

Suppose the pinhole is safe if the crushing pressure f_c is not greater than $2\,f_t$, then $d = \frac{1}{2}\,a/t$, or d must be equal to the width at the narrow part of the bar. The calculation is of course based on assumption, but it indicates why plate specimens with pinholes often give trouble by breaking through the ends.

With cast-iron test pieces the ends may be thickened, and then a smaller diameter of pin suffices. With wrought iron, cheeks may be riveted on to increase the bearing area.

Sometimes a number of smaller pins are used instead of one large pin. The objection to this is the great difficulty of drilling a number of holes so accurately that all the pins bear equally. Some specimens tested in this way break through the pinholes at sections very much larger than the middle of the bar, clearly showing a want of uniformity of bearing of the pins.

110.—*Friction Grips.*—In the *Journal of the Society of Arts,* vol. li., 1837, there is a description of what are termed 'nippers' for iron bars by Mr. J. Kingston, of Woolwich Dockyard. These nippers appear to be precisely the friction grips used at the present time for holding test bars. The shackles consisted of two iron blocks with a rectangular hole, having the two opposite sides inclined. Two gripping pieces, or wedges, fitted in the mortice gripped the specimen. As the tension on the bar

increased, the pressure of the gripping pieces increased proportionately, in consequence of their sliding down the inclined

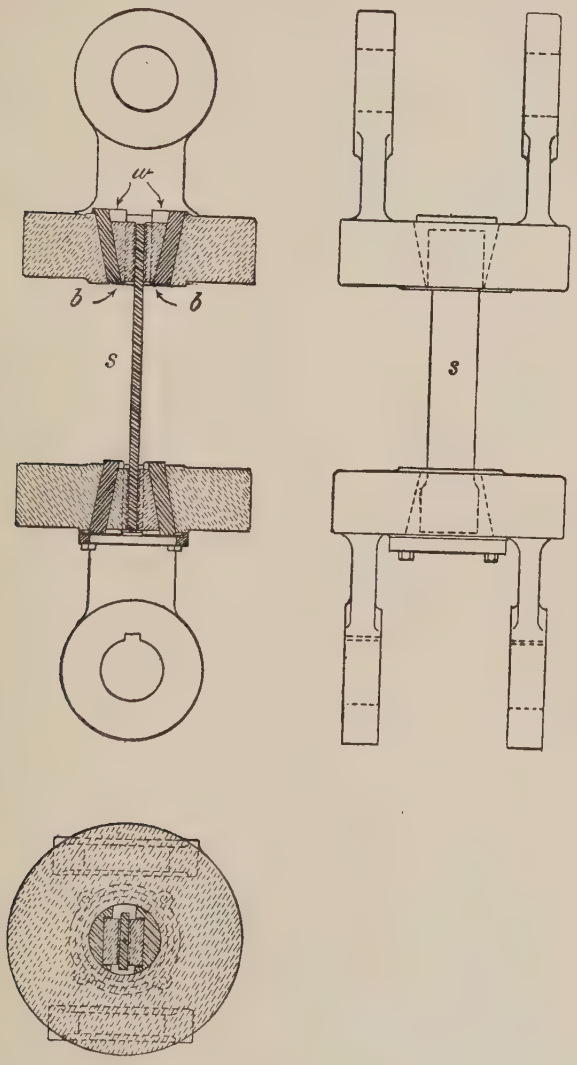


Fig. 91.

surfaces of the shackle. The inside of the gripping pieces was formed like a coarse screw-thread to give greater bite. The paper contains interesting details of experiments on

copper, Muntz metal, and iron bars made with these nippers.[1]

About 1860 the author used, at Sir W. Fairbairn's suggestion, some wedge grips of a similar kind. These were for cylindrical bars, and were made in three parts, like the cone keys at one time used for fixing pulleys on shafts. The wedges had a taper of 1 in 8, and fitted in a conical hole in the shackle.

Fig. 91 shows a shackle for wedge grips designed by Mr. Wicksteed, and not unlike the shackles used in many machines. The hardened-steel wedges with serrated faces

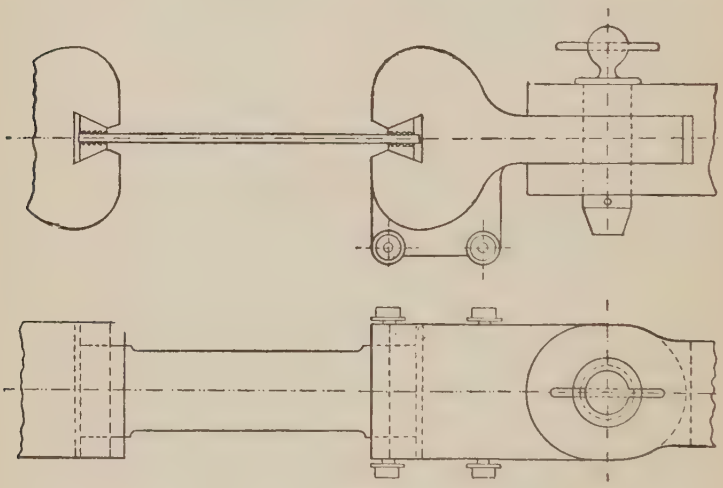


Fig. 92.

are seen at *w*, with the test bar *s* between them. These wedges have a slope at the back of 1 in 6. They are held in slots in two conical pieces *b*, which fit a conical hole in the shackle. These seatings allow the wedges to swivel, so as to hold test bars with faces not quite parallel. For round and square bars V-shaped grooves are formed in the face of the wedges.

Fig. 92 shows the arrangement of the wedge-grip shackles in the Werder machine. This shackle differs from those most used in this country: (1) in the shortness of the wedges;

[1] Sir Henry Trueman Wood pointed out this very early record of testing appliances to the author. The grips are figured in Barlow's *Strength of Materials*.

(2) in the slot in the shackle being open at the ends, so that any width of plate can be held. On the other hand, there is no provision for fairly holding test pieces, the faces of which are not parallel.

Riehle's Wedges.—In order to ensure the coincidence of the tension with the axis of the specimen, Messrs. Riehle Brothers, of Philadelphia, adopt a plan different from that used in this country. The shackle A, fig. 93, has a rectangular recess, so that the wedges which grip the specimen cannot swivel. There would, therefore, with ordinary flat-faced wedges be a likelihood that the wedges would grip the specimen more on one side than the other; in fact, if the specimen were thicker on one side they would inevitably do so. To

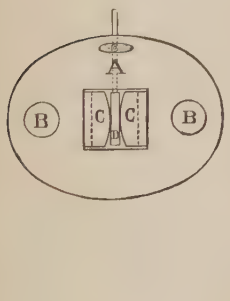
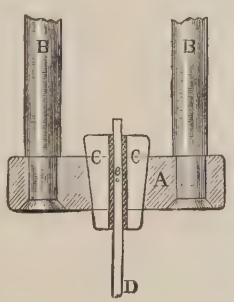


FIG. 93.



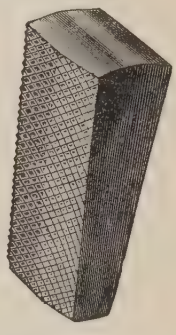


FIG. 94.

avoid this the wedges c c are made with a round face. Fig. 94 shows on a larger scale the form of one of Riehle's wedges.

111. *Shackles of the Smaller Emery Testing-machines.*—These are as original and ingenious as other details of the machine. Fig. 95 shows the shackle. *g* is the end of the press ram, or yoke, to which the shackle is to be attached. *f* is a nut forming part of the shackle. In the shackle two oblique cylindrical holes are bored, forming the seats for the sliding wedge pieces *b*. In these wedge pieces are fitted the various gripping pieces *c*, to suit flat plates of different thicknesses or round or square bars. The wedges *b* slide so that their faces are perfectly parallel. The gripping pieces are cylindrical, so that they can adjust themselves to plates of unequal thickness. The wedges *b* are not, as in other machines, loose, but form a permanent part of the shackle;

a toothed rack is formed on the side of them, engaging a pinion driven by the shaft h, so that they can be moved forward to grip the test piece. A ratchet and click prevents the slacking back. The wedges are traversed by a bar d carried by a rod e, which is pressed by a spring, against which the rotation of the shaft h moves them. Under f is an elastic packing to prevent injury by shock. The gripping pieces c are each in two parts, the back part being roughened with teeth, the front part plain. This allows a certain stretch of the specimen in the length of the gripping pieces, and at the same time holds them by a double bite. This prevents fracture of the test piece inside the shackle.

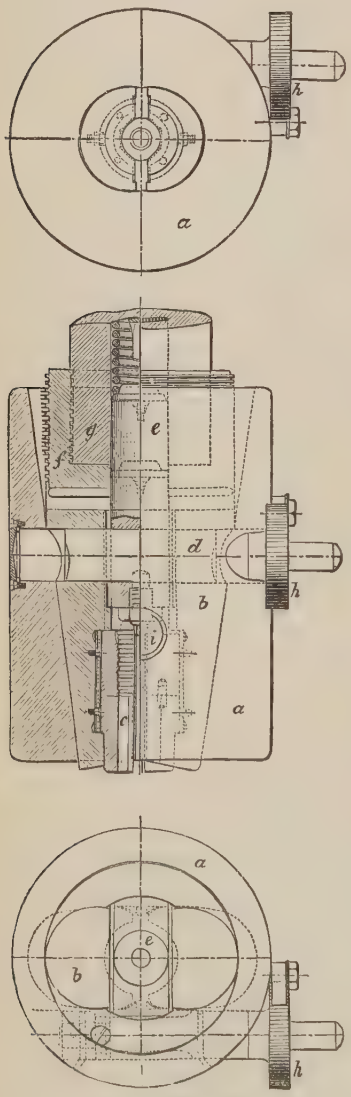


Fig. 95.

112. *Colonel Maillard's Grips.*—In the Maillard machine very convenient grips are used in the form of two half-rings n, n, fig. 96, screwed on the outside. The test bar is formed with shoulders at the ends. A pair of grips enclose the shoulder, and these are then screwed into the shackles of the machine.

113. *Shackles with Spherical Bearing-surfaces.* — For accurate experiments, especially for experiments on the modulus of elasticity, the coincidence of the tension with the axis of the bar is of great importance. It is best secured by carrying the bar on spherical bearing-surfaces.

The easiest way of supporting round bars is to form a screw-thread on the ends, and then fix on the bar a steel nut

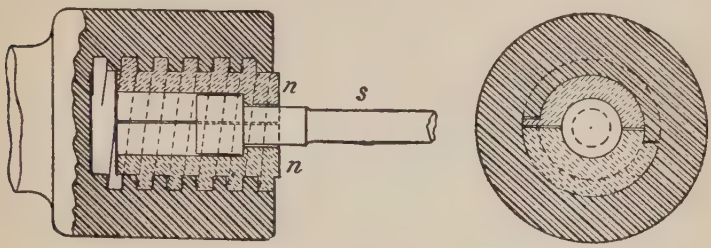


Fig. 96.

with hardened spherical face. Fig. 97 shows two arrangements the author has used. The screwing of the end of the test bar, which should be done in the lathe, is tolerably inexpensive. The steel nuts may have the forms shown, and they rest on steel rings which drop into the conical recess of the ordinary shackles. Cast-iron specimens are conveniently tested in this way, the screwed end being made rather extra large.

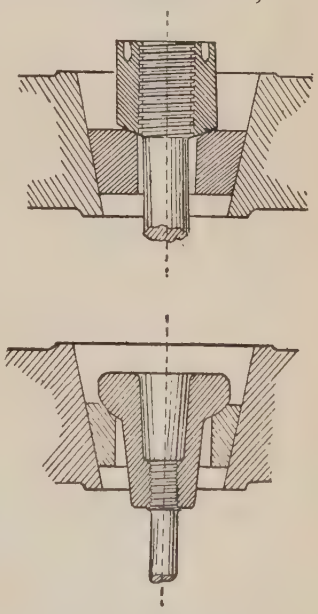


Fig. 97.

Spherical Seatings for Bars with Shouldered Ends.—The most satisfactory form of test bar for very accurate tension experiments is that adopted as the standard form in Germany. The round bar is turned in the lathe, leaving square shoulders at each end. As a seating for these shoulders two half-rings may be used, as shown in fig. 98. The author has used both forms. In one the displacement of the half-nuts during the test is impossible. But even with the other form, which is simpler, displacement does not occur. The half-rings should be of hardened steel.

Fig. 99 shows the shackles used in the machine of the Grafenstaden Engine Co., of Mullhouse. Two hinged boxes

grasp the test bar, which is formed with shoulders. Between the shoulders of the bar and the boxes, half-rings with spherical seats are inserted, so that the bar may swivel into the line of pull.

114. *Bauschinger's Tension Shackle for Specimens of Wood.*—Fig. 100 shows a cast-iron shackle

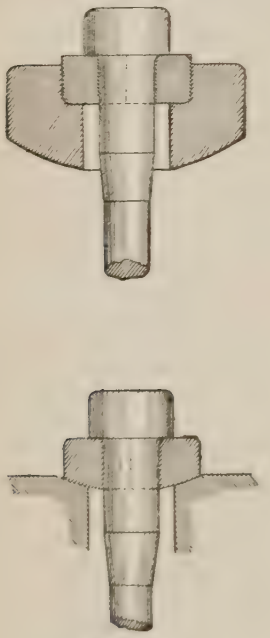


Fig. 98.

for specimens of timber used in Bauschinger's researches. The dovetailed end of the shackle fits in to the ordinary tension shackle of the testing-machine. The shackle is in two halves, and the specimen is centred by the set screws. In order to get a uniform distribution of stress in the neighbourhood of the shoulders, two thin wedges, or keys, are driven in at the back of the specimen.

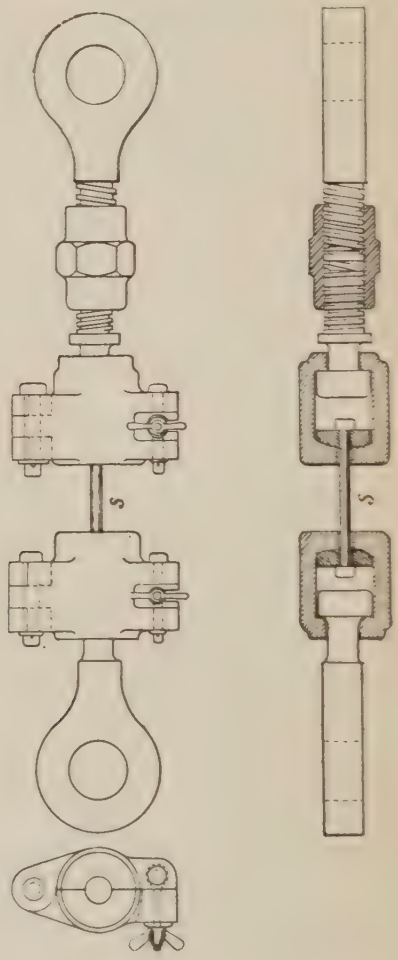


Fig. 99.

115. *Rope Shackles.*—The most satisfactory way of holding wire ropes for tension tests is to open out a portion near the end, place it in a socket, and cast a block of fusible alloy round the opened out portion. Fig. 101 shows a wire thus

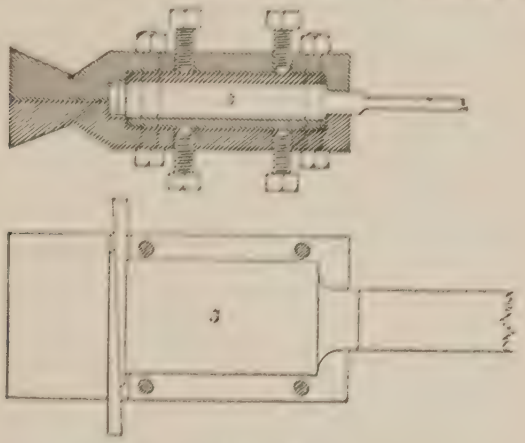


FIG. 100.

treated. The rope is wound with wire for a short distance near the end, the end strands are opened and any hemp cut away. The separate wires are then bent over and tinned, and care is taken that the rope is placed axially in the shackle. Finally, a block of alloy is run into the socket. Tetmajer[1] has used for the alloy a mixture consisting by weight of 80 parts tin, 10 parts copper, and 10 parts antimony. For ropes of harder steel, an alloy 9 parts lead, 2 parts antimony, 1 part bismuth.

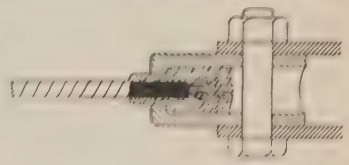


FIG. 101.

II. SHACKLES FOR OTHER TESTS

116. For accurate compression tests the test specimen must have parallel plane surfaces to which the crushing pressure is applied. To compensate for any inaccuracy of parallelism of surfaces of blocks or shackles, a spherical joint

[1] *Mitth. der Anstalt zur Prüfung von Baumaterialien* (Zurich), Heft 4, 1890, p. 234.

with free motion in all directions is interposed between shackle and test block. Fig. 102 shows a crushing shackle, designed by the author for short specimens. There *s* is the specimen, a cube of stone, for instance, which rests between the two parts of the shackle. The pull on the shackles exerts a crushing force of equal amount on the stone. The

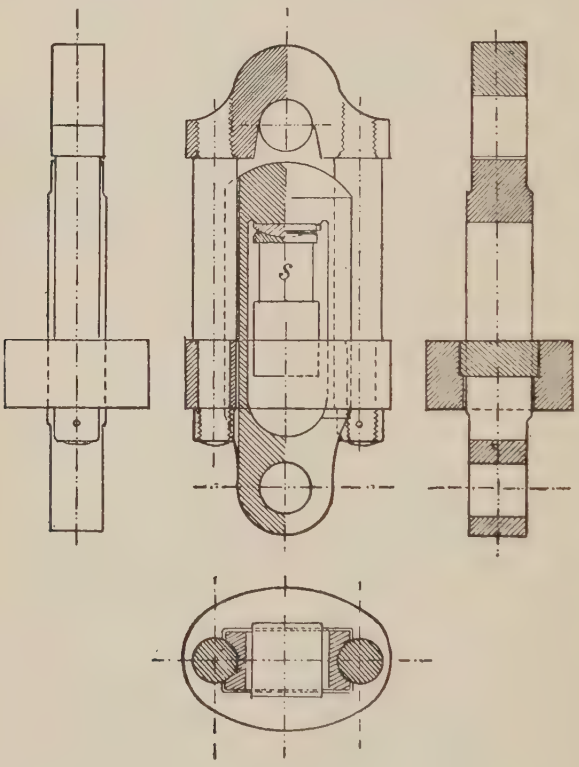


Fig. 102.

shackles are guided by the side bolts, so that the opposite faces remain parallel. To distribute fairly the load on the stone block, which may be, to a small extent, out of truth, a cup-and-ball distance piece, with well-lubricated surfaces, is placed between the upper face of the stone and the shackle.

117. *Torsion Shackle.*—Fig. 103 shows a form of friction grip used by Prof. Kennedy for holding specimens subjected to torsion; *s* is the specimen, held between two V-shaped

fixed jaws and a third movable jaw. This last is centred eccentrically to the curvature of its surface, so that the slight rotation of the specimen, tending to turn the jaw, produces a considerable frictional grip.[1]

In some torsion machines the test bar is made with a turned middle part and square ends. This is expensive, and wastes a good deal of material. The author has used for torsion tests the form shown in fig. 104. The test bar is turned from end to end, the ends rather larger than the middle part, and taper. A pair of hardened square steel nuts fit over the taper parts, and are fixed by keys. The test bar with its nuts drops into rectangular recesses in the torsion testing-machine, and is at once accurately centred. The test bar is cheaply produced in the lathe from a bar not much larger, the keyways being milled out. The nuts and keys are not injured in the process of testing. A set of nuts with taper holes of different sizes is used for test

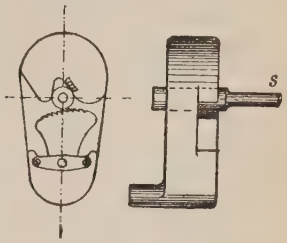


Fig. 103.

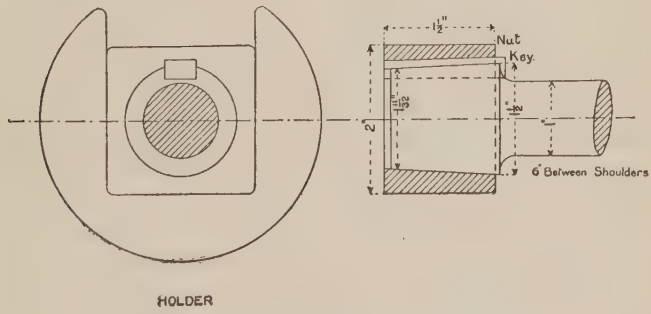


Fig. 104.

bars of different diameters. They all fit into the same recesses in the testing-machine.

118. *Transverse or Cross-breaking Shackles.*—Fig. 105 shows shackles for transverse tests supplied with the machine of Messrs. Buckton. A vertical machine lends itself less conveniently to transverse testing than a horizontal machine, but, on the other hand, no slides interfere with the accuracy

[1] 'Iron and Steel,' by P. V. Appleby, *Proc. Inst. Mech. Eng.*, vol. lxxiv.

of the test. The shackles shown are steel castings. The specimen *s s* (in the figure a rail bar) is shown supported

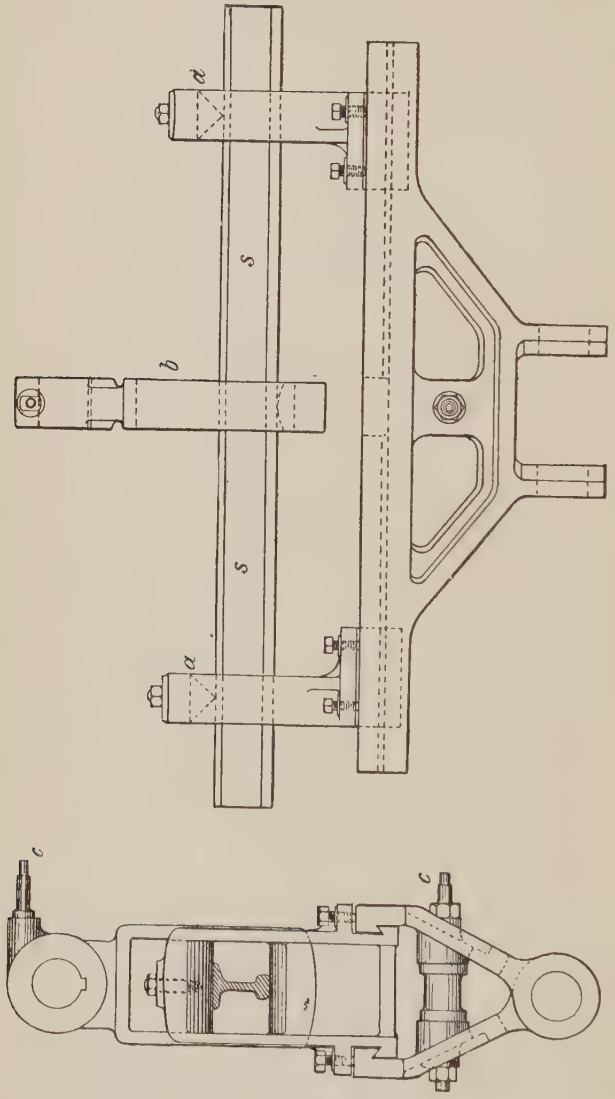


Fig. 105.

between two standards *a a*, fixed on the lower shackle, and the centre shackle *b*. The standards *a a* can be adjusted through a limited range for different lengths of span. There are

rough knife-edges at the points of support. The shackle shown is intended for loads up to 50 tons.

119. *Shearing Shackles.*—Fig. 106 shows a simple form of shearing shackle used in the Werder machine. The shackle

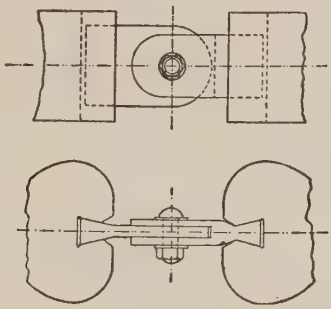


Fig. 106.

is formed as to be held in ordinary tension shackles. The rivet or bolt to be sheared is in double shear.

Wicksteed's Single-shear Shackle for Metals.—Fig. 107 shows the arrangement. The bar to be sheared is held in

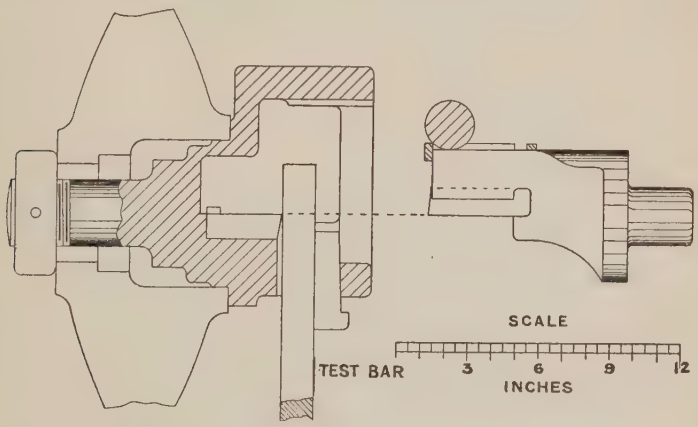


Fig. 107.

the left-hand shackle by a wedge, which presses it against one knife-edge. The other knife-edge is carried on the right-hand shackle which is guided, partly by its cylindrical form, which loosely fits the other shackle, partly by a loose roller which reduces the friction on the upper surface where

the pressure is greatest. The load is applied to these shackles in the testing-machine as in compression tests.

Figs. 108, 109, show a shackle designed by the author for shearing cylindrical bars such as rivet bars. The specimen *s s* is placed in the hole through three hardened steel discs, A, B, A, which it fits. Then the middle disc is forced down by the plunger P P. The discs are placed in the shackle and centred by the screwed nuts C C. *a* is a pin for holding up the plunger when adjusting the discs. The bar to be sheared cannot spread laterally as it fits the discs, and a satisfactory shearing action is obtained approximating to the conditions of practical use.

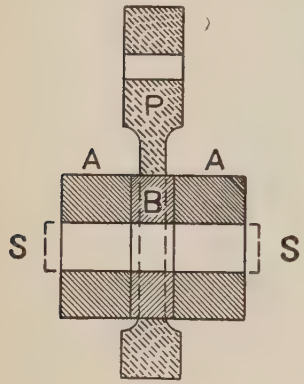


FIG. 108.

Fig. 110 shows a shearing shackle for flat bars designed by Mr. E. G. Izod.[1] In this *a a* is a stiff cast-iron frame carrying hard steel plates, *b b*

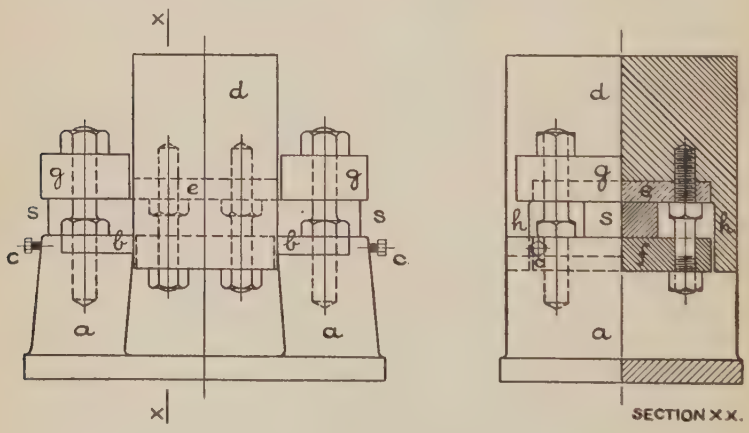


FIG. 110.

ground for cutting edges. The test bar *s s* lies on these and is gripped by the plates *g g*. A cast-iron block *d* slides

[1] *Proc. Inst. Mech. Eng.*, 1905.

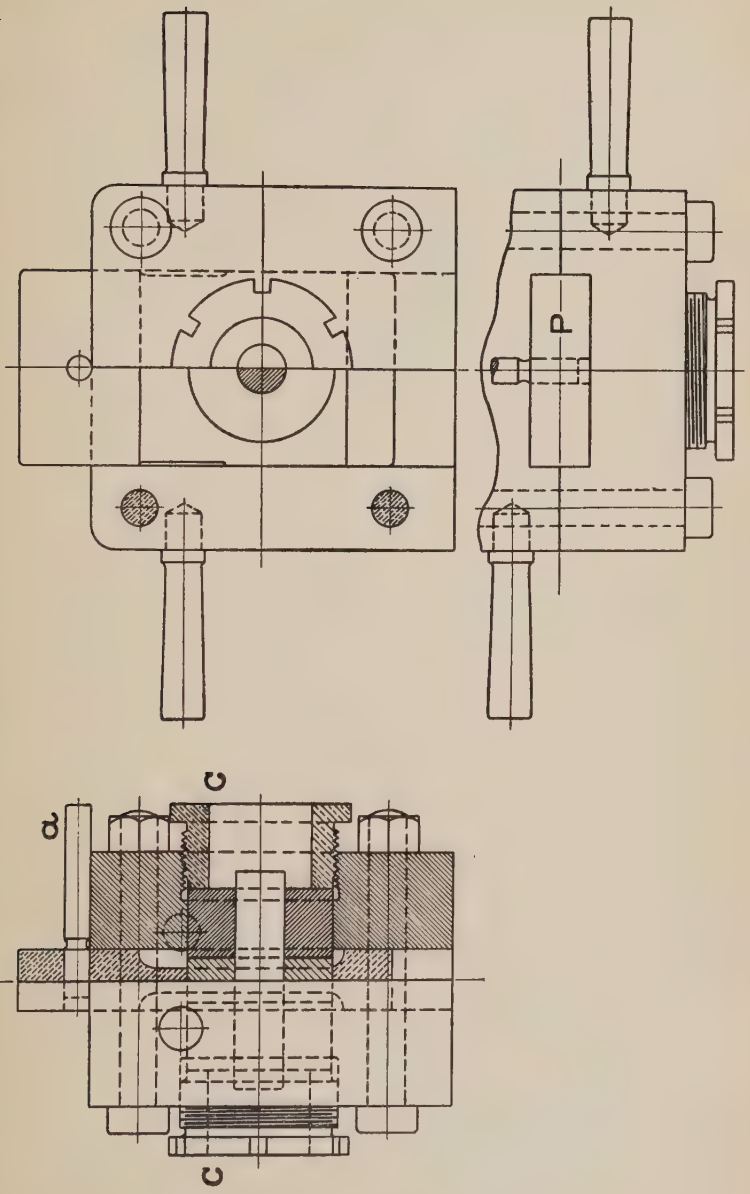


FIG. 109.

between the supports *a a* and carries a hard steel plate *e* with cutting edges. The test bar is also gripped to this by a cap and bolts. The object of the firm gripping of the test bar is to get rid of bending, and Mr. Izod describes his results as pure shear. But it is doubtful if in any shackle hitherto designed the fracture is really a pure shear.

The Author's Single-shear Shackle for Wood.—In the case

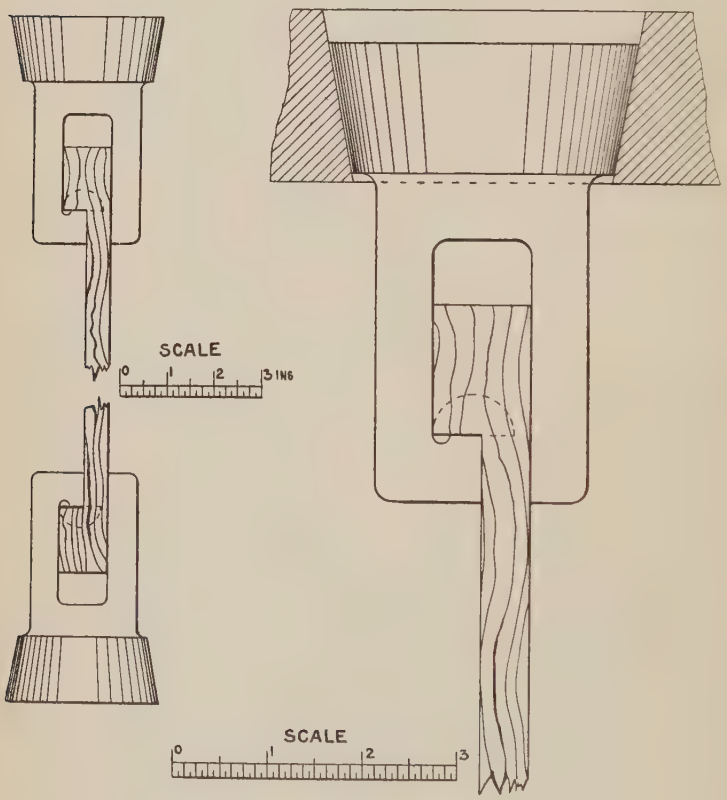


Fig. 111.

of timber, the resistance to shear along the grain is an important practical constant. To determine this the author has used the shackle shown in fig. 111, which fits into the conical seatings of the shackles for tension bars. The blocks holding the wood test bar are of cast iron. The shearing

surfaces at each end of the wood bar are about 4 sq. ins. in area. The line of pull of testing-machine is coincident with the shearing planes, and any bending of the timber is prevented by the planed cast-iron cheeks into which the specimen fits. The specimen is put into the shackles sideways. The test specimens are very easily prepared and fitted to the shackles.

CHAPTER VIII

IMPACT TESTS

120. For a long time rough empirical impact tests have been made by dropping a heavy weight on a bar supported at each end. The quality of the bar is determined by the number of impacts it sustains before breaking or before the deflection exceeds a fixed limit. Such tests are commonly made in the case of rail bars and railway axles. It has been noticed in some such cases that bars which behaved well in ordinary tensile tests were weak in resisting impacts, and there is a general impression in the minds of some engineers that the resistance to impact is specifically different from resistance to statical loads. In the case of used and worn rails the resistance to impact is sometimes very small, but in that case it is almost certain that the low resistance is due to minute fissures in the rail head induced in service.

There are undoubted cases, happily rather rare, in which steel which has passed all ordinary statical tests has shown brittleness, and has failed in service in a manner difficult to explain. Some writers have supposed that such material has some quality which has been termed *fragility*, not indicated in statical tests. Broadly, fragility is the property of breaking with little deformation and a small expenditure of mechanical work. It has been often supposed that such a quality is more likely to be discovered by impact than by statical tests.

121. *Impact Tests of Unnotched Bars.*—So far as ordinary unnotched test bars are concerned, the results of experiment, though not absolutely consistent, do not appear to show that there is any marked difference in the amount of work expended in breaking a bar statically or by sudden impact. The work done in a statical test can be determined from the area of an autographic diagram; that in an impact test by ascertaining the difference of the energy of the striking body

before and after impact. Martens concludes that in impact tension tests deformations are produced in exactly the same way as by slow tension. Mr. Hatt (Am. Soc. for Testing Materials) concludes that there is little difference in the total elongation or the unit work done in fracture, whether this be brought about in the space of ten minutes or of one hundredth of a second. Stanton's results are similar. M. Considère, however, experimenting on wires broken by a single impact, found that when the velocity of impact exceeded a certain limit, a change took place in the behaviour of the material. But later experiments by Charpy at still higher velocities have not confirmed this. The bars were 13·8 mm. diameter and 100 mm. gauge-length. The residual energy of the striking body was determined by the crushing of copper cylinders.

Comparison of Impact and Slow Tension Tests on Two Qualities of Steel (Charpy)

Mark	Elastic limit, *kilog.*	Breaking stress, *kilog.*	Elongation per cent.	Work done in fracture in *kgm*
		Slow tension.		
A	30·1	42·1	32·0	179·5
B	30·0	44·1	31·5	185·0
		Impact tension (fall, 47 m.).		
A	—	—	37·0	190
B	—	—	38·0	200

The work expended in impact was only approximately determined, but it does not appear to differ much from the work of fracture in slow tension.

122. *Notched Bar Tests.*—Charpy, Lechatellier, Fremont and others have sought a means of detecting the obscure property supposed to be the cause of unexplained fractures of steel, by impact tests of bars so notched as to limit the plane of fracture and to prevent contraction of area. The impact test has the special advantage that the work of fracture can be determined more simply and easily than by any other method. Notched bar impact tests have been made by simple tension and by bending bars supported at each end or encastré at one end. It does not seem proved that one of these methods is better than the others, but

M. Charpy concludes that as a supplement to the ordinary statical tension test, notched bar bending tests are most convenient. The data accumulated appear to show that notched bar impact tests do furnish information not given in ordinary tests, though the correlation of this with dangerous qualities in steel is not fully established. The mode of fracture in a notched bar test appears to be different from that in an ordinary test. M. Lechatellier suggested that fracture in steel might, according to circumstances, take place across the network of perlite or through the grains of ferrite; that is, the fracture might be intercellular or intracellular. But investigation so far seems to show that both methods of fracture occur together.

To show the difference between plain bar and notched bar tension and bending tests, M. Charpy has given the following results on four steels:

Comparison of Plain Bar and Notched Bar Tests (Charpy)

Mark	Ordinary tensile tests				Notched bar impact tests	
	Elastic limit, *kilog.*	Breaking stress, *kilog.*	Elongation per cent.	Work of fracture, *kgm*	Tension, total work in fracture, *kgm*	Bending work in fracture, per sq. cm. *kgm*
A	30·1	42·1	32·0	180	84	44
B	30·0	44·1	32·0	185	78	3
C	32·1	45·1	31·0	192	74	20
D	36·1	53·5	25·0	181	63	19

M. Charpy has indicated that while there is no agreement between the total work of fracture in tension tests and that in notched bar tests, there is some agreement in the work done after local contraction begins in a tension test and that in notched bar tests. Anyway, the impact notched bar tests, especially the bending tests, bring out striking differences not shown in the ordinary tests.

In some cases impact tests are made by a series of blows, the resistance of the bar being measured by the number of blows or the total energy expended before fracture. But in most of the tests of notched bars they are broken by a single blow, and the difference of energy of the striking body before and after impact is taken as the work of fracture.

123. *Machines for Impact Tests.*—In some machines a vertically falling weight is used. The energy before striking is calculated from the height of fall corrected for the friction of the guides. The residual energy is deduced from the compression of springs on which the weight falls after

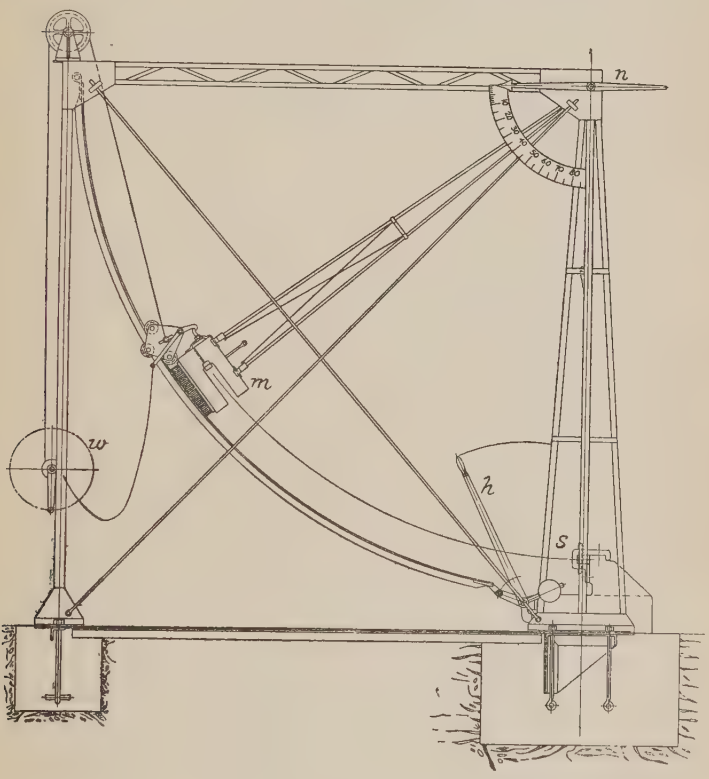


Fig. 112.

breaking the bar. More commonly a pendulum is used, and the work of fracture is calculated from the difference of the height of the swing before and after striking. Guillery has used a rotating fly-wheel driven electrically. The test piece is carried on a sliding anvil, so that it can instantly be moved in front of a knife-edge carried by the fly-wheel. The energy absorbed is calculated from the difference of speed of the fly-wheel before and after striking. A tachometer consisting of a small centrifugal pump raising water in a

graduated tube is used to determine the speeds. Two such instruments have been constructed, the energy of the fly-wheels being 60 and 200 kilogram-metres at 300 revs. per min.

On the whole the swinging pendulum apparatus and a test bar supported at each end form the most satisfactory arrangement. Fig. 112 shows a machine of this kind constructed by Charpy. The pendulum hammer weighs 170 lbs., and with a fall of 10 feet has a striking energy of about 1,700 foot-lbs. and a striking velocity of 26 feet per second. The striking mass m is flattened to pass between the anvil jaws, and is cut back so that the striking edge coincides with the centre of mass. The suspension is light and rigid, formed of tubes braced with wires. At impact, the centre of percussion is sensibly on the axis of the test bar to lessen vibrations and reaction at the support. A needle, n, frictionally fixed and moving over a graduated arc, is entrained by the pendulum in its return after impact, and indicates the height of rebound and residual energy. The test bar s is carried on two supports and struck at the centre. The pendulum is attached to a carriage, raised by a winch w, and released by a catch. After impact the arc a is raised by the handle h and acts on a brush on the pendulum, acting as a brake to arrest the oscillations.

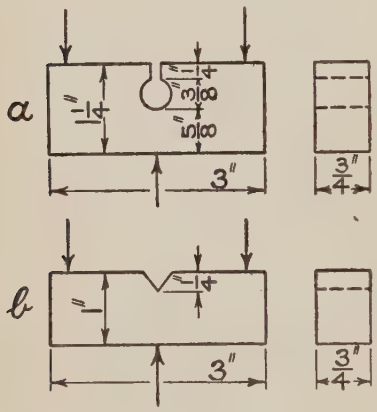


Fig. 113.

The test bars are 80 to 200 mm. long, and of a cross-section varying for different materials. For steel the cross-section is 30 × 15 mm.

A smaller impact apparatus also constructed by Charpy has a striking energy of 211 foot-lbs., a striking velocity of 17 feet per second, and a height of fall of 4·65 feet.

The friction of the apparatus is found by observing the decrease of the arcs of oscillation. If H is the height of fall, and H_1 the height to which the pendulum returns, the work

of friction per oscillation is $\frac{1}{2}$ P (H — H_1), where P is the weight of the pendulum.

These machines can also be used for impact tests in simple tension. The test bar is fixed at one end to the hammer, and at the other is screwed into a crossbar, which is arrested by the anvil as the hammer passes through.

124. *Izod Machine.*—Mr. Izod described at the British Association in 1903 a small pendulum impact machine in which notched bars are held at one end and broken by the pendulum at a fixed leverage. The general arrangement is that the weight or hammer is suspended by a rigid rod swinging from a centre. The hammer moved out to a fixed height is allowed to fall on the free end of the test bar gripped in a vice. The striking energy of the hammer is 23 foot-lbs. The height of fall is such that the test bar is broken at one blow. A recording arrangement measures the height to which the hammer rises after breaking the specimen. If H_1 and H_2 are the heights of swing before and after testing, and W the weight of the hammer, then W (H_1 — H_2) is the energy expended. The test bar is 2 inches long, $\frac{3}{8}$ inch wide, and $\frac{5}{16}$ inch thick. The notch is V-shaped and 0·05 inch deep. The following are some of the results:

Material	Yield stress, tons per sq. in.	Tensile breaking stress, tons per sq. in.	Elongation in 2 in. per cent.	Work absorbed in fracture by impact ft. lbs.
Steel from forging	18·6	33·4	33·0	2·5
Steel from forging	20·5	39·3	28·0	2·2
Steel from forging, oil tempered	20·5	39·3	28·0	0·7
Special steel . . .	37·0	52·0	25·0	16·9
Stud steel	—	31·0	30·0	6·9
Naval brass	—	26·3	19·0	3·7
Naval brass	—	30·3	28·0	5·5

125. *Form of the Notched Bars.*—Two forms have been most generally used, shown in fig. 113. In *a* the notch is formed by drilling a hole tangent to the centre line and sawing through to the surface. In *b* the V-notch is used with an angle of 50° or 90°, and the bottom of the notch is either very sharp or slightly rounded. Bars with angular notches are weaker than with rounded notches, but great precision in the shape of the notch does not seem to be important. The work of fracture, however, increases with

the radius of the curve at the bottom of the notch. Notches 1 mm. wide made with a saw will answer in many cases. Le Blant and others found that the shape of the V-notch, whether made with tools new or worn, had little influence. But an acute-angled notch gave more easily comparable results than others.

126. *Reduction of the Results of Impact Tests.*—In the case of impact tensile tests the work expended is calculated per cubic unit of the stretched part of the bar, and the law of similarity must be observed, that is, the length and diameter of the test piece must have a fixed ratio. But a standard has not yet been fixed.

The case of bending impact tests is more difficult. The phenomena of bending after the elastic limit is passed are complicated, and ordinary bending equations do not apply. It has been common to calculate the work expended per unit of area of the fractured section, but this is purely empirical and inexact, except when applied to test bars of the same form. Revillon has shown that for the same area of section, the work of fracture increases with the span of the test bar, and for a given span is only the same for sections of the same dimensions. But results reduced to unit area of section become comparable if the homologous dimensions of the test bar and the span have a constant ratio.

Mr. Harbord's Research.—Mr. Harbord made impact tests on a series of steels of various quality by five different methods of impact testing. Of these the Fremont [1] method approached most nearly to the pendulum method, which has proved most satisfactory with bars notched in the middle and supported at the ends. But the impact was by a falling weight, the residual energy being measured by springs, and the test bars were very small, having only 7 mm. × 10 mm. section. It would have been desirable to make tests with a pendulum machine and a larger test bar. Mr. Harbord's general conclusions are, that in all the methods there are excessive variations of results in tests of the same material, and that for different materials the differences in the results are inexplicable. He states that the claim of supporters of impact testing is that it indicates latent defects not shown by static tests, but when tensile tests of two steels show a difference of tenacity of only 4 tons per sq. in. with approximately the same elongation, and the impact tests show

[1] *Trans. Inst. Mech. Eng.*, 1908.

the relative brittleness to be as 100 to 16 by one method, and as 100 to 21 by another, one has very seriously to consider the value of these tests.

The author is disposed to think that the discrepancies found by Mr. Harbord are, in part at any rate, due to the smallness of the test bars used in the Fremont and Izod tests.

127. *Influence of Temperature in Impact Tests.*—Guillet has shown that for steels annealed at 800° C., the work of fracture increases with the temperature to 200° C., then falls and finally rises again. The maximum fragility was found at 475° C., or incipient red heat. Charpy found that the work of fracture of steel increased to some temperature between 100° and 200° C., decreases to a minimum at 400° to 500° C., and finally rises again till a red heat is reached. Some special steels, such as chrome-nickel steel, are less weakened at low temperatures than ordinary steels, and the work of fracture rises with increasing temperature, even up to 400° or 500°.

Dr. Stanton's Method.—Dr. Stanton has devised a new method of impact testing. The test bar is ½ inch in diameter, is grooved at the centre and is supported on knife-edges 4½ inches apart. It is struck about 100 times per minute by a hammer weighing 4½ lbs. falling a distance varying at will up to 3½ inches. Between each blow the bar is turned through 180°. The total work required to fracture the bar is calculated from the number of blows recorded by a counter and the height of fall. A very ingenious machine for carrying out this test is made by the Cambridge Scientific Instrument Company. The method is ingenious and appears to imitate the conditions in which machine parts break in service in consequence of vibration and shock. But further investigation is necessary to determine the bearing of the results on the constructive value of materials.

CHAPTER IX

MEASURING-INSTRUMENTS

Ordinary measuring-instruments are required to determine the dimensions of test bars. In some cases the deformations (elongations, deflections, &c.) can be observed accurately enough by the same instruments. For the accurate measurement of strains, however, special measuring-instruments are required.

128. *The Graduated Straight-edge.*—Steel straight-edges of different lengths, graduated on the edge, are used for several purposes. For the rougher tests dimensions may be callipered, and the callipers placed on the graduated straight-edge. Extensions of ductile materials can be measured in a similar way. Two slight centre punch marks are made on the bar, and the distance between these is taken by a beam compass, which is then placed on the graduated straight-edge. The differences of successive measurements are the elongations. Convenient graduated straight-edges are made by the Brown & Sharpe Manufacturing Company, of Providence, U.S.A. These have graduations into $\frac{1}{10}$ and $\frac{1}{100}$ths inch, and into millimetres and fifths of millimetres.

129. *The Straight Vernier Calliper.*—The beam compass of the draughtsman is very commonly graduated along the beam, and a vernier is fixed on the sliding head. The fault of the beam compass, however, is the springiness of the points, and want of truth of the sliding surfaces of the beam. A vernier calliper is a beam compass with very rigid points and a metal beam. Fig. 114 shows the construction of a vernier calliper as made by Messrs. Brown & Sharpe. A steel straight-edge is bent down at *b* to form one leg. On this slides very accurately the sliding head B, carrying the second leg *a*. For conveniently adjusting the position of the sliding head B there is a third slide C, which can be clamped to the bar, and from which the position of B can

be adjusted by a fine-pitched screw. The slide carries a vernier.

The most convenient graduation for English measures is for the scale to be divided into tenths, and each tenth into five. Each small division reads twenty thousandths. If now on the vernier a length of nineteen small divisions is divided into twenty, the vernier will read thousandths of an inch.

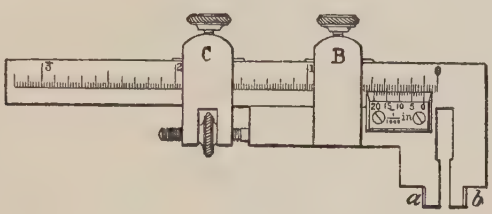


Fig. 114.

The outside diameter, or width, of bars is obtained by placing them between the jaws *a b*, and sliding the moving head till contact with gentle pressure is obtained. The calliper should be held lightly in both hands, and by slight movements it is easy to determine if the jaws are square with the bar to be measured. No excessive pressure must

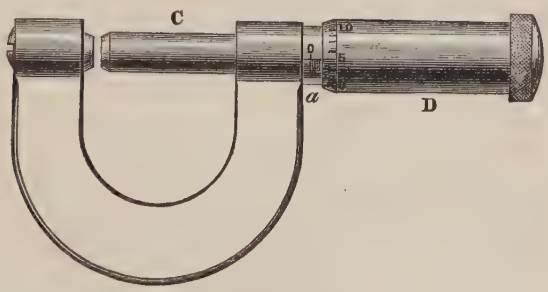


Fig. 115.

be used, or the instrument will be injured. Inside diameters of rivet-holes and similar measurements may be obtained by using the rounded outsides of the jaws *a b*. There is then a fixed quantity to be added to the reading on the scale. Some callipers, however, have two verniers, so placed that one reads outsides and the other insides.

130. *The Screw Micrometer.*—This instrument (fig. 115) is useful for determining the dimensions of the smaller test

bars. At one end of a bent frame is a fixed abutment, at the other a cylindrical bar C, moved by a fine-pitched screw. By turning the sleeve D, the bar C advances to or retires from the abutment. An object to be measured is placed in the jaws, and C is advanced till there is contact with gentle pressure. Some tact is required, and it should be remembered that a force applied to the sleeve produces a much greater pressure between the jaws. There is a graduation along the straight cylinder at *a* into tenths of an inch and quarter-tenths, and the edge of the sleeve D is itself graduated into twenty-five divisions, each of which corresponds to a movement of the jaw of $\frac{1}{1000}$ inch. It is quite possible to read the scale by estimation to one-fifth of $\frac{1}{1000}$ inch. But although this reading is easy, it is not equally easy to ensure the delicacy of touch required for so great accuracy. In the Brown & Sharpe micrometer calliper, the adjustment to zero, if the instrument wears, is effected by withdrawing the sleeve D and applying a small wrench to a nut inside. The instrument should be tried occasionally to see whether, when screwed home till the faces of the jaw touch, the scale really reads zero. If not, adjustment is required. The accuracy of this instrument depends entirely on the accuracy with which the fine-pitched screw is cut. When obtained from really a trustworthy maker the screw can generally be relied on to read accurately to the nearest $\frac{1}{1000}$ inch. Beyond this degree of accuracy, however, no screw can be trusted which has not been independently tested. Usually these instruments take between the jaws either 1 inch or 2 inches at most.

The accuracy of vernier callipers and screw micrometers may be tested by means of the ordinary inside and outside gauges in use in the workshop.

131. *Professor J. E. Sweet's Screw Micrometer.*—This instrument (fig. 116) is made by the Syracuse Twist Drill Company. It has a ratchet-threaded measuring screw, the working face of the screw-thread being normal to the axis of the screw and the back face inclined. The tops of the thread, both in screw and nut, are removed, so that after wear a perfect bearing is still obtained by closing the split nut. A slight looseness of the nut will not affect the measurement, on account of the square bearing of the thread. The screw and nut are of equal length (3 inches), to ensure equality of wear. The screw is moved by a sleeve provided

with a milled head, and held between washers, one of steel and the other of felt, to produce an adjustable friction, so that equal pressure may always be obtained between the measuring points. The index bar projecting over the divided circle is adjustable. The pitch of the most carefully made screw is more or less variable, and no two screws are absolutely of the same pitch. This error is corrected by inclining the index bar forward for a screw of too fine pitch, backward for one too coarse. Each instrument is adjusted by the makers to a standard 1-inch distance piece. The index bar is mounted on a split sleeve, threaded upon the

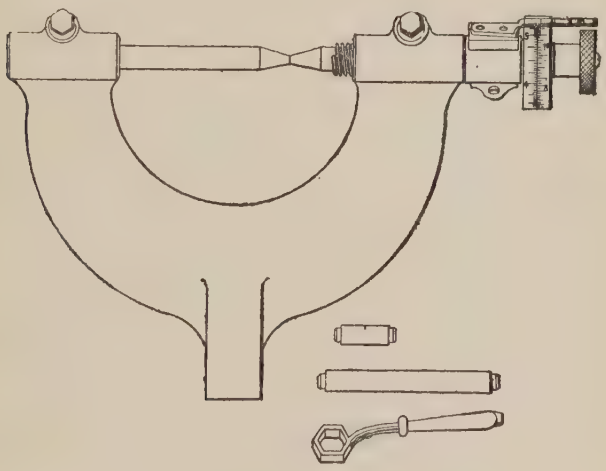


Fig. 116.

extended end of the measuring nut with a thread of corresponding pitch. This allows the index bar to be thrown backward or forward to a convenient position for reading, or even turned a half-revolution, if desired, to measure work on the lathe and read the dimension in that position. The above, which may be termed the head-gearing, is used only for determining the fractional parts of an inch. Whole inches are measured by the aid of standard distance pieces, furnished with the instrument. The tail-spindle is unclamped, drawn back, and a distance piece inserted, and the spindle again clamped. No special pains need be taken to do this accurately, as the final adjustment is effected by setting the index bar and its sleeve. The milled head is double, being

graduated for $\frac{1}{1000}$ inch, and for binary fractions as small as $\frac{1}{64}$ of $\frac{1}{32}$, or $\frac{1}{2048}$ inch. The milled head by which the screw is turned is mounted freely on the spindle, and held between a washer of felt and one of steel, dowelled upon the end of the spindle, and tightened by an adjusting screw. The friction thus produced secures uniform pressure between the measuring points, and eliminates the 'personal equation.' A variation of $\frac{1}{10000}$ inch can be recognised. The capacity of the instrument is 0 to 4 inches.

132. *Whitworth's Millionth Measuring-machine and Workshop Measuring-machine.*[1]—These are fixed instruments, of heavier and much more accurate make than the ordinary screw micrometer. The screw has 20 threads to the inch, the screw wheel 200 teeth, and the micrometer wheel is

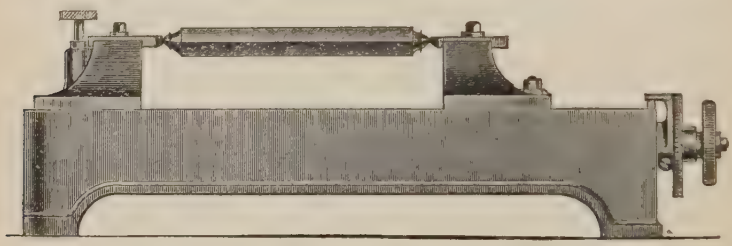


Fig. 117.

divided into 250, so that each division represents $\frac{1}{1000000}$ inch. The end of the fast headstock and the end of the movable headstock are true parallel planes. The ends of the piece to be measured must also be true parallel planes. In measuring to an accuracy beyond $\frac{1}{10000}$ a feeling piece is used. This is a piece of steel about $\frac{2}{10}$ inch thick, with parallel faces. It is introduced between the bar to be measured and the fast headstock. When proper adjustment has been reached, the movement of one division of the micrometer wheel will set fast the feeling piece.

Fig. 117 shows a machine of this type of American construction (Richard's machine), with a standard test piece in the jaws. The machine consists of a solid bed, something like a lathe-bed, with two headstocks, one fixed, the other moved by the accurate fine-pitched screw. The screw has a graduated head, and sometimes a vernier also. The machines

[1] 'On Linear Measurement,' Sir J. Whitworth, Science Conferences, South Kensington, 1876, p. 216.

are guaranteed to be correct to $\frac{1}{10000}$ inch. They read to $\frac{1}{25000}$ inch, but, without special means of ascertaining the pressure at the point of contact, such accuracy of reading is fallacious.

133. *Comparator for Length Measurement.*—In ordinary micrometers and callipers an error arises from the straining of the instrument in consequence of the variable pressure exerted between the measuring points. The author constructed some years since a form of instrument in which the pressure between the measuring points is constant. Fig. 118 shows the instrument, which has two headstocks, one with a

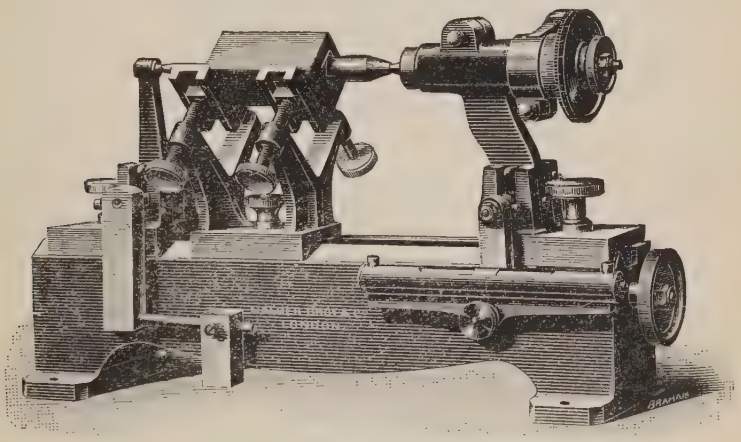


Fig. 118.

micrometer screw. The headstocks rest in V's, and are pressed towards each other by the action of a weight. Each also carries a very sensitive level. Usually the back headstock is clamped when levelled. The micrometer screw is then turned till the other headstock resting against the bar to be measured is level also. Standard bars of 1 inch, 2, 3, 4, and 6 inches are used. The comparator is first set to the length of one of these, and a reading taken. Then the bar to be measured is placed between the headstocks and a reading taken. From the two readings the difference of length from that of the standard bar is obtained. In the figure a standard bar is shown between the headstocks. It is carried by adjustable V-shaped supports which permit it to be set exactly level with the measuring points.

INSTRUMENTS FOR MEASURING STRAINS

134. In experiments on the elastic properties of materials it is necessary to measure the strains or deformations for different stresses. Thus, in tensile tests the elongations are measured, in torsional tests the twists, in bending tests the deflection.

In commercial tests of the quality of ductile materials, such as wrought iron and steel, only the ultimate permanent deformation is measured, and since this deformation is considerable, comparatively rough measurements are sufficient. Thus, if a soft steel bar is broken by tension, the permanent stretching of an 8-inch length may amount to 2 inches. An error of even $\frac{1}{50}$ inch in measuring this would be only 1 per cent. of the elongation, and that is accuracy enough for practical purposes. For somewhat more rigid material, such as wrought-iron plates, the extension is less, and it is desirable to make the measurement more closely. But even in that case no very refined measurement is practicable, because of the difficulty of fitting together the broken pieces. To ascertain the strains in ductile materials during the progress of a test, after the elastic limit is passed, somewhat rough measurements are also sufficient. But it is altogether different in observing the strains within the elastic limit. A mild steel bar, 10 inches long, is stretched less than $\frac{1}{1000}$ inch when the elastic limit is reached. For an accuracy of 1 per cent. the error of measurement must, therefore, not exceed $\frac{1}{10000}$ inch; and measurement to this degree of accuracy is more difficult than is commonly supposed. If the true elastic limit is to be determined, measurements to at least $\frac{1}{100000}$ inch are necessary. The smallness of this quantity may be realised by the aid of an illustration due to Sir J. Whitworth: $\frac{1}{100000}$ inch is only $\frac{1}{400}$ of the thickness of a sheet of thin foreign letter-paper. In the case of standard measures of length, with bars of the most suitable form, the measurement, even to this degree of accuracy, is comparatively easy. But measurements of deformation have to be made on test bars of a form less suited for measurement and under conditions of some difficulty.

In the case of test bars, a difficulty of measurement arises out of the occurrence of a change of curvature of the bar during the test.[1] The bar may initially have a small curvature,

[1] The discussion following is taken from a paper by the author on 'Measuring Instruments used in Mechanical Testing,' *Phil. Mag.* March 1887; *Proc. Phys. Soc.* 1887.

and be straightened by the load; or, if the load does not act accurately along the axis of the bar, it may become curved during the test. Suppose a bar curved like the bar in fig. 119 in the plane of the paper. If the bar straightens by loading, the distance between a and b will increase, not only by the amount of the elongation, but by the difference of chord and arc length $a\,b$. Suppose two clips fixed on the bar normal to its axis, and measurements taken between two points a_2, b_2. By straightening of the bar the clips will become parallel, and the distance $a_2\,b_2$ will be lengthened by the alteration of inclination of the clips still more seriously. It is important to notice that if the points a_2, b_2 had been taken on the other side of the bar, an opposite error would have arisen, the distance being shortened by the straightening of the bar. Consequently, we may infer at once that the mean of measurements on opposite sides of the bar will be much more free of error due to curvature than any single measurement.

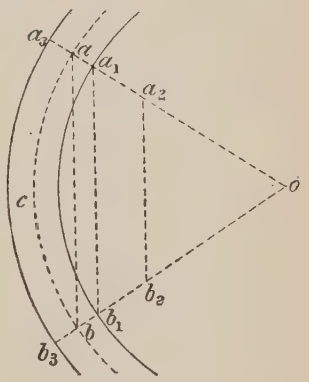


FIG. 119.

Suppose a, b are two points on the axis of a bar, initially bent in the plane of the paper. Let arc length $a\,b = 2c$, chord $a\,b = 2a$, versed sine $= h$. Then—

$$c = \sqrt{(a^2 + \tfrac{1}{3}h^2)}, \text{ nearly.}$$

If now measurements are taken on a straight scale between a and b, and the bar straightens by tension, it will have an apparent elongation $2\,(c-a)$, due merely to change of curvature, and this will enter as an error into the measurement of the extensions. For instance, suppose the chord length $a\,b$ is 10 inches, and the versed sine of the curve $\frac{1}{50}$ inch. The bar would then have a curvature probably as great as could occur in a reasonably good test bar. Then the arc length would be 10·000026 inches, and an error might arise, from the straightening of the bar during a test, of 0·000026 inch. This, however, is a quantity too small to be of importance in ordinary measurements of extension. Consequently, if measurements were really made between points on the axis of the bar, it does not appear that serious error would

arise from any probable amount of initial curvature of the bar.

In fact, however, in all measuring instruments the measurement is made at a distance from the axis of the bar. Under the best circumstances the bar would be measured at two points a_1, b_1 on its surface, which, in the straightening of the bar, would move apart to a distance equal to the arc length $o\ b$, the lines $o\ a$, $o\ b$ becoming parallel. In most measuring instruments the case is much worse; the measurements are made between two points, a_2, b_2, rigidly connected with the bar, and the error introduced into the measurements is the difference of the length $a_2\ b_2$ and the arc length $a\ b$. Since, as has been shown, the difference of the arc and chord length $a\ b$ is very small, it will be a sufficient approximation to say that the error of measurement will be the difference of

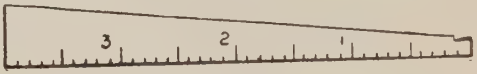


Fig. 120.

the straight lengths $a_2\ b_2$ and $a\ b$. Let $a\ a_2 = x$, and $o\ a = r$. Then—

$$\frac{a_2\ b_2}{a\ b} = \frac{r - x}{r} = \frac{a^2 + h^2 - 2\ h\ x}{a^2 + h^2}.$$

If, as before, $a\ b = 2a = 10$ inches, $h = \frac{1}{50}$ inch, and $x = 2$ inches, then $a_2\ b_2 = 9{\cdot}968$ inches. Then, if by the straightening of the bar the lines $o\ a$, $o\ b$ become parallel, an error is introduced in the measurements of 0·032 inch: a very appreciable quantity, even in rough measurements of elongation. The error is more than 1,000 times as great as it would be if the measurements were really taken directly at the axis of the bar. If the measurements are taken on the surface to the bar at a_1, b_1, the error will be less. Thus, if $a\ a_1 = x = 0{\cdot}375$ inch, we get $a_1\ b_1 = 9{\cdot}994$ inches, and the error due to straightening would not exceed 0·006 inch: a quantity much less, but still large enough to be of consequence in elastic measurements. If the mean of measurements taken at points symmetrically placed on either side of the bar is adopted, the error due to curvature is nearly eliminated, the lengthening of the distance on one side being compensated by shortening on the other.

135. *The Wedge Gauge.*—The wedge gauge (fig. 120) is

a triangular plate, with slides sloping at 1 in 10, graduated along the longer side. If this is pushed between two pins, or shoulders, the distance between them can be read off on the scale, magnified ten times. Two loose pieces a, b (fig. 121) are clamped on the test bar, and the wedge gauge pushed between them. They are made to bite into the test bar slightly at two points on the test bar, at a distance l. As the test bar extends, the wedge gauge slips further in, and the differences of readings give the elongations to $\frac{1}{500}$ inch.

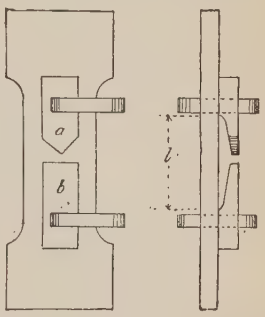


Fig. 121.

136. *Micrometer Screw Extensometer.*—A screw is equivalent to a wedge gauge in a more convenient form. It is virtually a wedge gauge wrapped round a cylinder. If $p =$ pitch of screw, $d =$ diameter of graduated head of the screw on which readings are taken, $\delta =$ the distance to be measured parallel to the axis of the screw, Δ the distance on the circumference of the head which corresponds to an axial movement δ, then—

$$\frac{\Delta}{\delta} = \frac{\pi d}{p},$$

$$\Delta = \pi d \delta / p.$$

Let the screw have 25 threads to the inch ($p = 0{\cdot}04$), and the head be about $2\frac{1}{2}$ inches in diameter, and divided into 100 parts of about $\frac{1}{20}$ inch each. Then each division corresponds to $\frac{1}{2500}$ inch, and can be read by estimation to quarter-divisions, or $\frac{1}{10000}$ inch. The accuracy of the instrument depends on the uniformity of pitch of the screw, which is often less accurate than it is intended to be. Differences of pressure at the point of contact cause differences of reading.

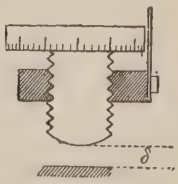
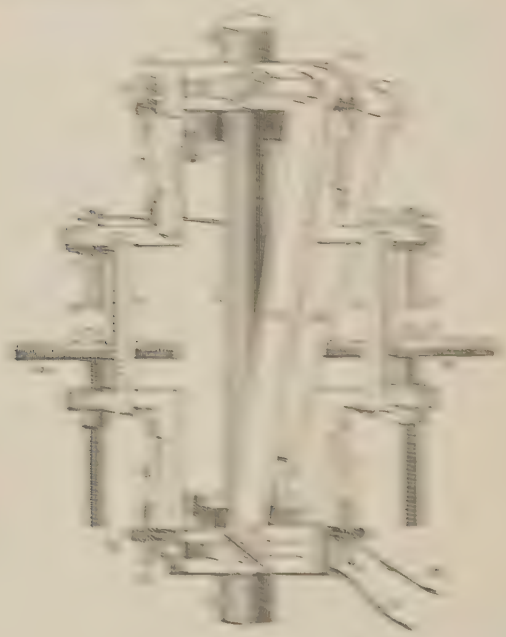


Fig. 122.

Professor Thurston[1] appears to have first used an instrument with two micrometer screws placed symmetrically on each side of the axis of the test bar. These screws were carried in a clamp fixed on the test bar, and were brought

[1] *Materials of Engineering*, Thurston, vol. ii. p. 369.

[illegible] completed circuit and gave a signal.



[illegible]

[illegible] of two clips, or carrying frames, [illegible] knife-edges on each clip. As the distance between the clips increases with the extension of the specimen, the [illegible] is measured by two symmetrically placed micrometer [illegible]

[illegible]

knife-edges at *c c*. The bars *d d* are used in fixing the clips initially at the right distance apart. They are then moved out of the way while the instrument is in use. Vertical scales *e e* are provided, as well as the graduation on the heads of the micrometer screws *m m*. Each of the frames is connected with an electric bell, a circuit being established when the point *f* of either micrometer screw touches the contact-plug *g*. To ensure proper adjustment in a plane normal to that of the micrometer screws, the centring screws *h h* are brought to bear on the surface of the test bar, after the rods *d d* have been thrown into gear, and the points of the micrometer screws placed over the centre of the contact-plugs. Then the centring screws are forced slightly into the test piece, so as to hold securely. After this, the side bars *d d* are gently removed and the electric wires attached. The plane of contact of the micrometer screws and contact-plugs is in the middle of the measured length. The author has used this instrument, but he has not found it satisfactory. It is very difficult to get contact of screw and plug without displacing the seating of the clips on the bar.

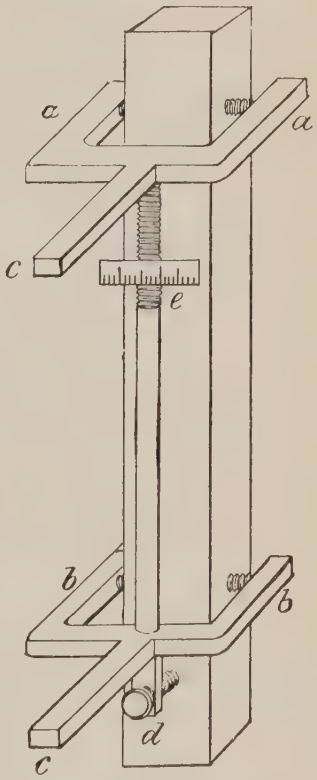


Fig. 124.

138. *Screw Extensometer with Levels.*[1]—Fig. 124 shows diagrammatically an arrangement the author has adopted, which obviates most of the difficulty of employing a micrometer screw. Two clamps grip the specimen between pointed set screws, *a a* and *b b*, at points on a plane passing through the axis of the bar. The lower clip carries the micrometer screw *e*, on the hardened point of which the upper clip rests. If, then, the clips are kept exactly normal to the axis of the

[1] *Proc. Physical Society*, vol. viii. p. 178, 1886.

test bar, the micrometer screw measures the distance between two points on the axis of the test bar—namely, the points on the intersection of $a\,a$ and $b\,b$ with the axis. Or, to put it another way, the micrometer screw being at the middle of the width of the clips, it measures the mean extension of the two sides of the bar. To set the clips accurately normal to the axis of the bar, they are provided with delicate levels. Before taking a reading these are adjusted. The lower clip is first set level by the adjusting screw d. Next, the upper clip is set level by the micrometer screw e; lastly, the reading is taken on the graduated head of the micrometer screw. Fig. 125 is a general view of the instrument applied to a flat test bar. $c_1\,c_2$ are clips; $l\,l$ levels; m the micrometer screw; r a bar of adjustable length which is fixed to the micrometer screw by a clip to suit different test bars. The instrument is easily fixed; the pressure on the micrometer screw is constant, being the weight of the upper clip; by having a set of bars r of different lengths the instrument is adjusted to any gauge-length; and the measurements are virtually measurements made on the axis of the bar, so that errors due to curvature are nearly eliminated. The instrument constructed reads to $\frac{1}{100000}$ inch.

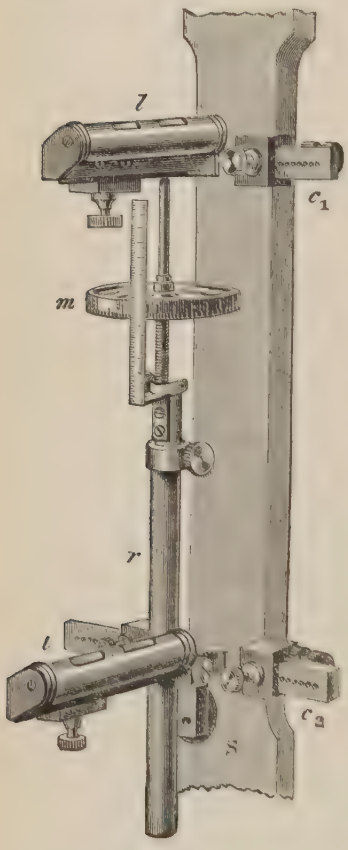


Fig. 125.

Figs. 126, 127, show an improved form of the instrument. A and B are the clips and levels; e the levelling screw; h the set screws for fixing the clips on the test bar; $g\,g$ screws fixing the set screw brackets on the clip, which is of V form, securing rigidity to the attachment of the brackets; a is the

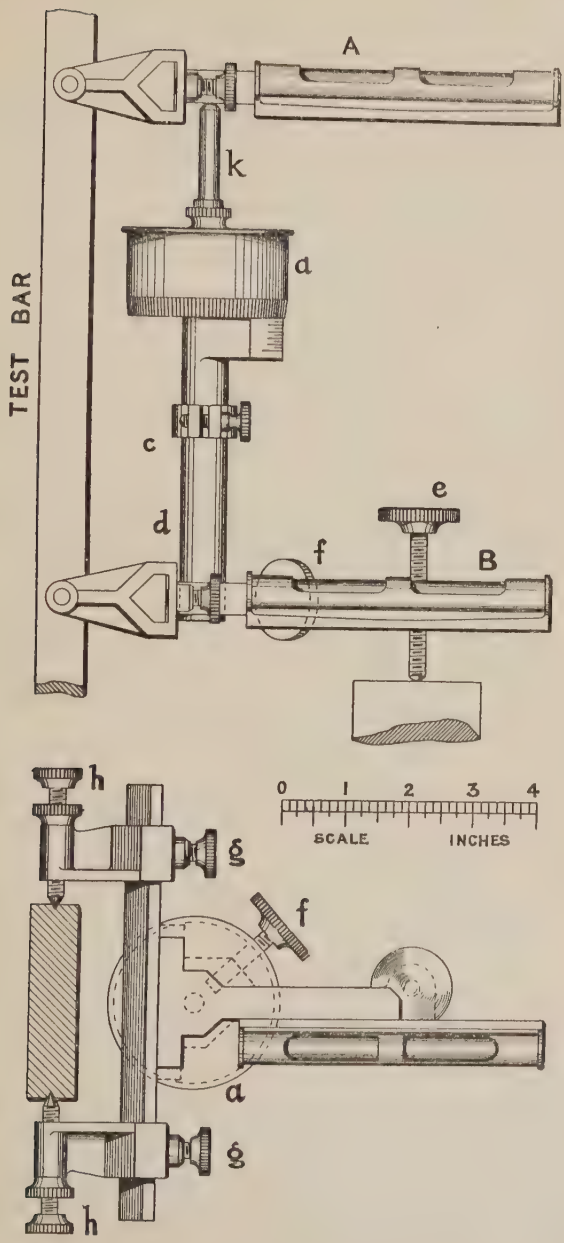


FIG. 126.

divided micrometer head, and the spacing bars [illegible] are [illegible] to the micrometer screw k by the clip a.

[illegible] The [illegible] — The [illegible] is an instrument

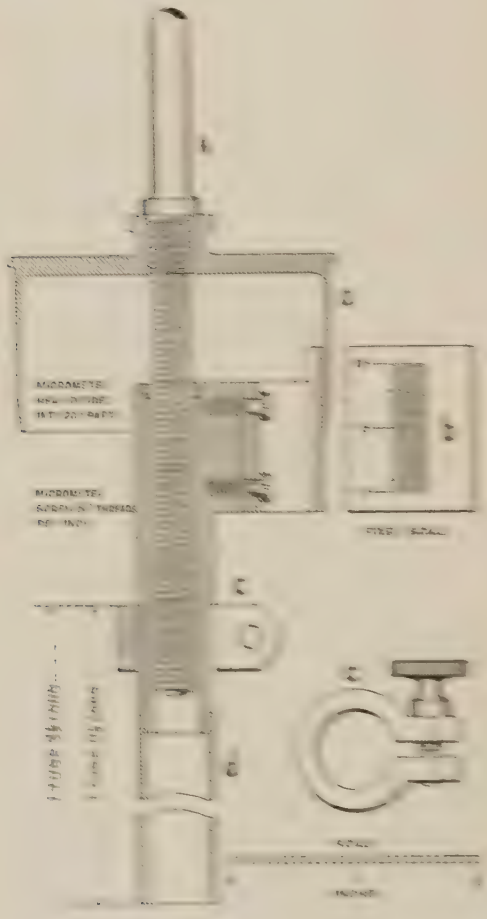


FIG. 127

for determining the difference of level of two points by a telescope sight. It may therefore be applied to determining the elongation of a bar under stress by reading the length between two [illegible] scratches before and after the stress is applied.

It consists of a telescope with cross wires, carrying a sensitive level, and sliding on a very accurately formed vertical slide. The slide is carried on a support, round which it can rotate. Suppose the axis of rotation adjusted accurately vertical, and the slide adjusted accurately parallel to the axis of rotation. Lastly, let the axis of the telescope be adjusted to the horizontal by the aid of its level-tube. Then if the telescope be set in succession on two points, and readings taken on a scale attached to the telescope-slide by a vernier attached to the telescope, the difference of the readings will be the difference of level of the points.

The cathetometer is for certain purposes valuable. The

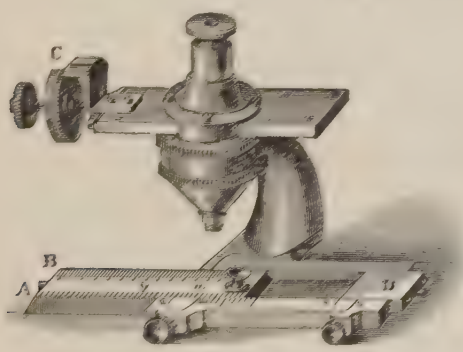


FIG. 128.

readings are taken from any convenient distance, without its being necessary to touch or even approach the bar to be measured. The measurements are taken directly on an accurate scale, and are absolute measures, not needing any reduction, and not depending on any other measurements. On the other hand, in determining elongations or deflections the cathetometer is laborious in use.

By means of a micrometer eyepiece, a cathetometer may be used to read to $\frac{1}{10000}$ inch. In connection with one of the testing-machines at Berlin there is a cathetometer with two telescopes, having micrometer eyepieces, so that both marks on the bar can be read on the cathetometer at the same time.

140. *Touch Micrometer.* — Every mechanic is accustomed to take dimensions in callipers with very great accuracy.

Hence it appeared that a process equivalent to callipering would be delicate enough even for measuring elastic extensions. The author constructed an instrument of this kind in 1883.

Suppose two clips fixed on a test bar in some way which strictly defines the length of bar, which in extending carries the clips. Let there be on the clips steel plugs in pairs opposite each other. If the distance between these plugs is callipered during a test, the amount of extension can be determined.

Fig. 128 shows a micrometer calliper. It consists of a frame having a sliding piece A, which can be fixed by a set screw. The piece D is merely an adjusting piece, ordinarily clamped, which can be replaced by a longer piece if necessary, to suit different lengths of test bar. Both the sliding pieces A and D have hard steel plugs at their ends. In use the instrument is held in the hand between the clips on the test bar, and the steel plugs brought into contact with those on the clips with gentle pressure. The slide is then clamped, and the reading taken.

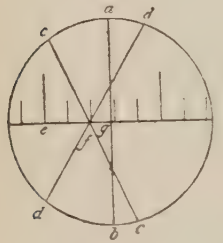


FIG. 129.

The sliding piece has two scales, A and B. The scale A is read by sight against a vernier on the frame to hundredths of an inch; the other scale is read through the microscope micrometer. Fig. 129 shows the field of view in the microscope: *a b* is a fixed cobweb, corresponding with the zero on the scale A. In the field is rather more than a tenth of an inch on the scale B, the tenths being divided into fifths of tenths (or fiftieths) of an inch. From the reading on the scale A the precise tenth in the field of view is known. Suppose that *e* reads on the fixed scale 2·2. Between *e* and zero *g* are two fiftieths and a fraction of a third. The point *f* therefore reads 2·24, and it only remain to measure the distance *f g*. This is done by bringing the crossed cobwebs to *f* by means of the graduated head C of the micrometer, when the number of tenths of thousands of an inch which measure *f g* is read off on the graduated head. The process is tedious to describe, but it is extremely simple in practice. Further, as the same tenth of an inch usually remains in view for the whole period of a test in which the elastic extension is measured, it is in general only

necessary to note the reading on the graduated head C after the first reading.

Cowper's Extensometer.—Mr. Cowper has described an extensometer used in testing long bars of the Kieff Bridge in 1850.[1] It consisted of a light iron tube about 4 feet long, with a small brass fork at each end which fitted against pins attached to the test bar. One fork slid on an accurate slide and carried a vernier. This fork was pushed home against the pin by a spiral spring.

141. *Lever Extensometers.*—Many instruments have been used in which the extensions of a bar are mechanically magnified by a lever. The defect of such instruments is that the extension is measured between clips often attached to the bar in an unsatisfactory way, and that, to obtain sufficient magnification, the short arm of the lever is so short that the range of indication is very small.

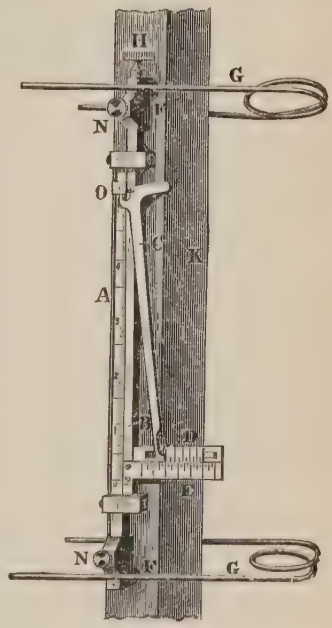


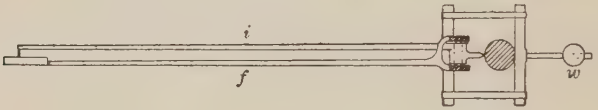
FIG. 130.

Col. Paine's Lever Extensometer.[2]—A neat and simple form of lever extensometer shown in fig. 130 was used by Col. Paine in tests made at the East River Bridge. The apparatus consists of two bars, A and B, arranged to slide parallel to each other. At one end of each bar there is a knife-edge F in a brass slide, and initially these knife-edges are adjusted to a known distance apart. The instrument is clamped to the test bar K by spring s G G, which press the knife-edges into small indentations of the bar. A lever C is fixed on the bar B. Its short arm bears on a projection O on the bar A, while its long arm moves a vernier D which slides in the projecting guide E.

Kennedy's Lever Extensometer.[3]—Professor Kennedy has designed and very largely used the simple lever extensometer

[1] *Proc. Inst. of Mechanical Engineers*, 1878, p. 256.
[2] Abbot, *Testing-machines* (Van Nostrand's Science Series), p. 86.
[3] *Proc. Inst. of Civil Engineers*, vol. lxxiv.; also lxxxviii. p. 24.

shown in fig. 131. This consists of a light frame *f* carrying a simple lever *i*. The two steel points, one on the frame *f*, the other on the lever *i*, are 10 inches apart. These are placed in centre punch marks on the specimen *s*, the apparatus being



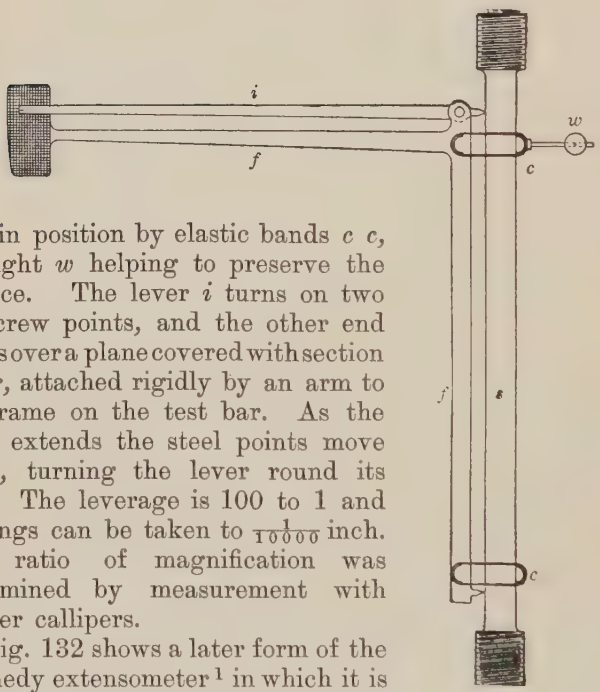


FIG. 131.

held in position by elastic bands *c c*, a weight *w* helping to preserve the balance. The lever *i* turns on two set screw points, and the other end moves over a plane covered with section paper, attached rigidly by an arm to the frame on the test bar. As the piece extends the steel points move apart, turning the lever round its axis. The leverage is 100 to 1 and readings can be taken to $\frac{1}{10000}$ inch. The ratio of magnification was determined by measurement with vernier callipers.

Fig. 132 shows a later form of the Kennedy extensometer[1] in which it is gripped on the bar at four points in an axial plane. A A is the test bar on which the extensometer is gripped on a 10-inch gauge-length. B B are the clamps and C C the clamping screws. Vertical arms on the clamps carry triangular frames E_1 E_2 by joints of thin steel F. Each triangular frame rests on the other clamp. Attached to E_1 is a block G, adjustable by a fine pitched screw H. This block

[1] *Engineering*, September 12, 1890.

carries a small cupped disc of hard steel J, which is thus rigidly attached to E_1, and therefore to one of the clamps. To E_2 is attached a light plate spring K, the free end of which

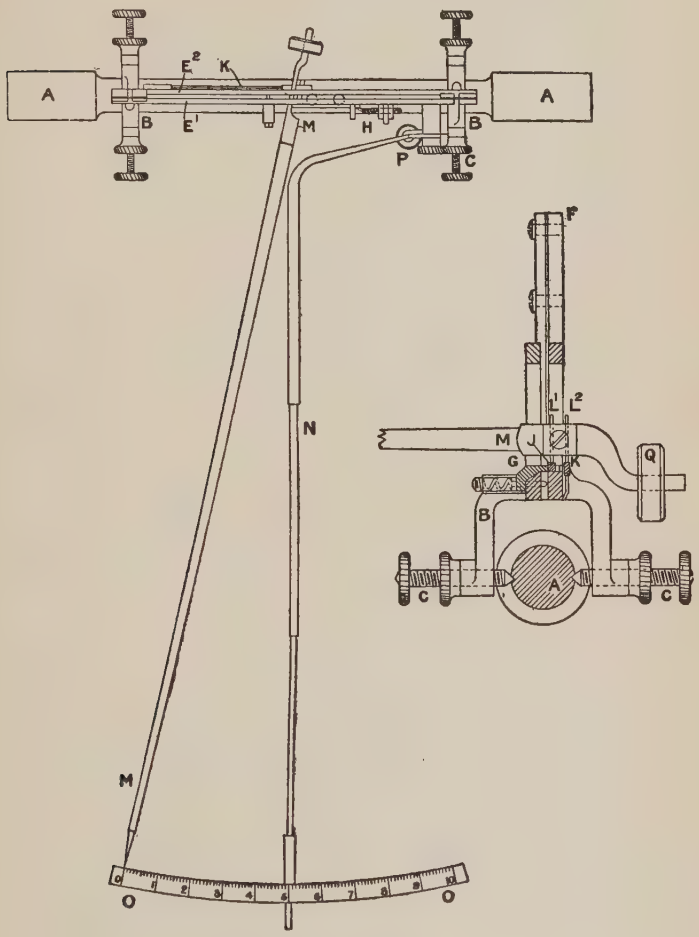


FIG. 132.

carries a cupped steel block corresponding to J. The free end of K can move to a small extent transversely, but longitudinally is rigidly attached to E_2 and the other clamp. When the test bar elongates, J and K move past each other. The movement is magnified by a light pointer M M, which rests by

steel points L_1 L_2 in the steel discs J and K. The movement of M M is read on a scale O O, carried by a rod N, attached by an adjusting screw P to the frame E_1. The instrument is calibrated by fixing it on vernier callipers; $\frac{1}{100}$ of an inch movement of M on the scale corresponds to an extension of $\frac{1}{10000}$ of an inch.

142. *Dupuy's Extensometer.*[1]—The object of this apparatus is to ascertain the alterations of length of different members of iron structures by loads. Assuming that a bar of iron is elongated or shortened $\frac{1}{10000}$ part of its length by stress in tension or compression of 1·27 ton per sq. in., it is possible to calculate from the observed alterations of length

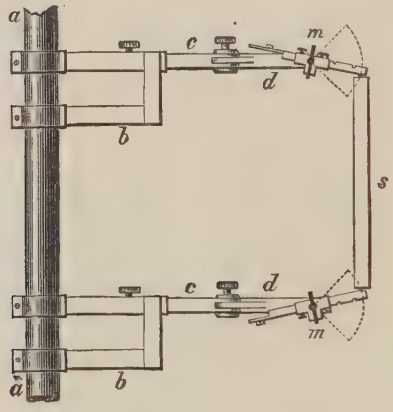


FIG. 133.

the stresses in the bars produced by the loads. To the bar to be tested a fulcrum pin is attached, on which works a lever arm, with a leverage of 20 to 1, terminating in a pointer moving over a graduated arc carried by the fulcrum piece. To the short end of the lever is jointed a bar 1 metre (3·28 feet) in length, a pin at the other end of this bar being also attached to the bar to be tested. With the proportions adopted, each millimetre of movement of the pointer on the scale corresponds to a stress of a kilogram per sq. mm. in the bar to be tested (0·635 ton per sq. in.).

143. *Differential Cathetometer.*—This instrument was exhibited by Dr. Heinrich Streinitz, of Gratz, at South

[1] *Ann. des Ponts et Chaussées*, 5th series, vol. xiv. p. 381.

Kensington in 1876,[1] and appears to have been used by him some years earlier in researches on the elasticity of wires. Dr. Streinitz appears to have originated a method of measurement which is extremely delicate. Fig. 133 shows the principle of the apparatus: *a a* is a stout glass rod carried by a heavy foot; on this are clamped the two frames *b b*; *c c* are rods sliding in the frames *b b*, and *d d* are jointed prolongations, serving to adjust the instrument; *m m* are light touch levers, which by weights or strings are kept in contact with the bar *s* to be measured.

These levers rotate in the plane of the sketch on pins at the ends of the bars *d d*, and each lever carries a mirror *m* perpendicular to the plane in which it rotates. Every movement of either end of the bar *s* will cause a rotation of the corresponding mirror. Suppose a telescope and scale so placed that the graduations of the scale are seen after reflection at the mirror in the telescope. Then, as either mirror rotates, the graduations will move in the field of the telescope.

Now let δ be the movement of one end of the bar to be measured, and Δ the corresponding change of scale reading. Let L be the distance of telescope and scale from the mirror, and r the radius of the lever m to the point of contact with the bar s. Then—

$$\Delta / \delta = 2\,\mathrm{L} / r$$

Now as r can be made as small as one centimetre, and L as much as 5 metres, the movement can be magnified 1,000 times. If a good telescope is used, tenths of millimetres can be read on the scale, and consequently the movement of the end of the bar can be determined to $\frac{1}{10000}$ millimetre. The difference of the movement of the two ends of the bar gives the change of length of the bar. It is obvious that the method of measurement is one of extreme delicacy. The apparatus in no way interferes with the free movement of the bar. Dr. Streinitz determined r by using a spherometer. The rod *a a* is of glass, on account of its small coefficient of expansion. Moreover, the glass tube may be filled with water and the temperature ascertained by thermometers. A correction for any change of temperature can then be applied.

[1] *Catalogue of the Special Loan Collection of Scientific Apparatus at South Kensington Museum*, 1877, p. 60.

144. *Bauschinger's Roller and Mirror Extensometer.*[1]—To Prof. Bauschinger belongs the credit of first systematically taking double measurements on opposite sides of a test bar. A pair of clips, formed like parallel vices, are clamped on the bar at a and b (fig. 134). These grip the bar between knife-edges. The clip b carries a pair of hard ebonite rollers d_1, d_2 on accurately centred spindles. The spindles are prolonged upwards and carry the mirrors g_1, g_2, which rotate in the plane of the figure as the spindles rotate. The rotation of the mirrors is measured by reading-telescopes e_1, e_2, and scales f at a distance of 10 or 15 feet. The scale-divisions seen by reflection in the mirrors cross the wire in the field of view of the telescope. The mirrors have vertical and horizontal adjustments for bringing initially the scale into the

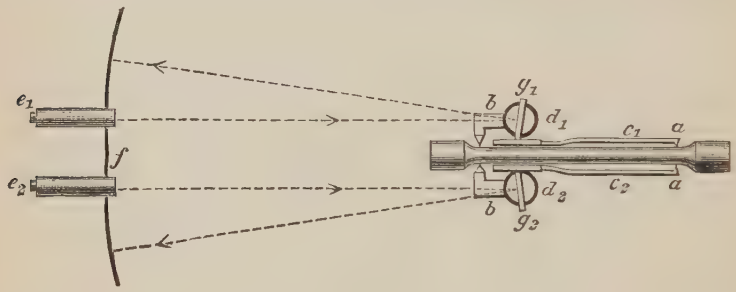


FIG. 134

field of view of the telescope. To turn the rollers d_1, d_2 proportionally to the extension of the test bar, the clip a carries a pair of spring pieces c_1, c_2, which touch the rollers d_1, d_2. The face of these spring pieces is slightly roughened by a file or by attaching a strip of the finest emery paper, and they turn the rollers by frictional contact. It will now be obvious that any extension δ of the distance between the vices a and b will cause a rotation of the mirror g through an angle δ/r, where r is the radius of the roller. The apparatus is equivalent to a lever apparatus having for small arm the radius of the roller g, and for long arm the double distance of the scale from the mirror. Suppose, for instance, as in one of Bauschinger's instruments, the radius of the roller is 0·3214 cm.

[1] *Maschine zum Prüfen der Festigkeit der Materialien, construirt von Ludwig Werder, und Instrumente zum Messen der Gestaltsveränderung der Probekörper, construirt von Joh. Bauschinger.* München, 1882. Also *Mittheilungen a. d. Mech. Tech. Laboratorium München*, Hefte 1 und 3.

and the scale distance 160·7 cm. Then the magnification of the extension is $(160{\cdot}7 \times 2) \div 0{\cdot}3214 = 1{,}000$. The scale is divided into fifths of centimetres. Each division has, therefore, in measuring extensions the value of $\frac{1}{500}$ millimetre, or about $\frac{1}{10000}$ inch. As it is possible to estimate tenths of divisions, the readings can be taken to $\frac{1}{5000}$ millimetre.[1]

Since in Bauschinger's apparatus there are two mirrors, two readings are taken, giving the extensions on the two sides of the bar. The mean of these is taken to be the true extension, free from error due to initial or induced curvature of the test bar.

Bauschinger used instruments similar in principle for measuring compression of stone, the lateral contraction of

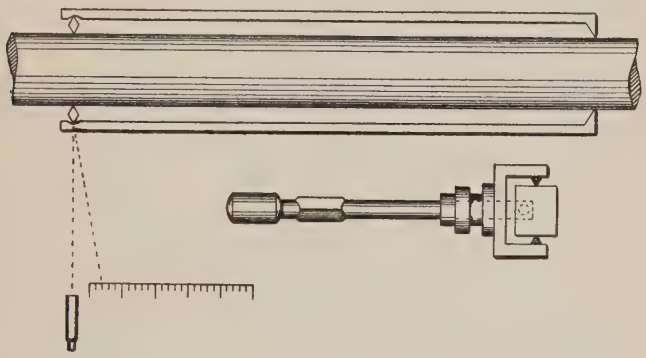


Fig. 135.

metals, &c. For rougher measurements the mirror and telescope are abandoned, and a light index-finger moving over a scale is substituted.

An apparatus similar in principle to Bauschinger's was used by Col. Flad in the tests of material for the St. Louis Bridge. This apparatus had, however, only one roller and mirror, which for delicate measurements is essentially defective.

145. *Professor Martens' Mirror Extensometer.*—This is a modification of the Bauschinger arrangement, and is an instrument of extreme sensitiveness and accuracy. Two light rods (fig. 135) pointed at one end are gripped to the test bar by a light spring. At the other end these rest not directly on the

[1] In practice straight scales are used and a correction applied to give the equivalent reading on a circular scale.

test bar, but on two lozenge-shaped prisms. As the bar extends these prisms rotate, and the angular rotation is measured by a telescope mirror and scale, as in the Bauschinger arrangement. The lower figure shows one of the prisms with its counter-weighted end and stem carrying the mirror. Two readings are necessary, one for each prism. The mean is the true extension. The width between the knife-edges of each prism is about $l = 4{\cdot}5$ mm. The distance L from scale to mirror is taken 250 l or 500 l. The scale is graduated in millimetres. The extension e, corresponding to a difference of scale readings R, is approximately

$$e/\text{R} = l/2\text{L},$$

but a correction is necessary which can be taken from a table. It is stated to be possible to read with this extensometer to $\frac{1}{250000}$ of an inch. In modified form it can be used for compression of stone cubes, &c.[1]

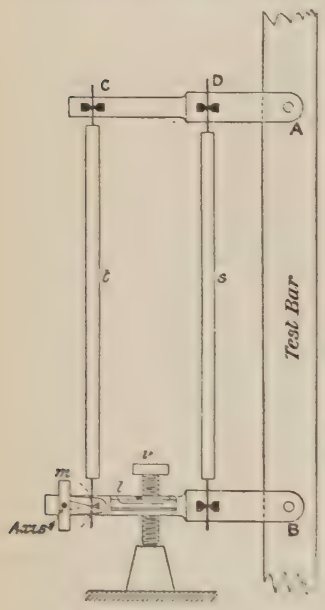


FIG. 136.

146. *The Author's Mirror Extensometer.*—This is a modification of Bauschinger's arrangement, by which the mean extension of the bar is obtained from a single reading. Fig. 136 is a diagrammatic sketch of the instrument. A and B are two clips, each fastened to the test bar by a pair of set screws, which grip the bar at four symmetrical points on its middle plane. The lower clip has a sensitive level l and an adjusting screw v by which it is kept level when a test is going on. The upper clip is supported from the lower clip by a strut s. To avoid any slack the strut s has at its ends two very thin pieces of watch spring, which are gripped between a set screw and a knife-edge. The lower clip carries a mirror m pivoted between two set screws. The

[1] Martens, *Materialienkunde*, i. 52. An investigation of the theory of the instrument is given by G. H. Knibbs, *Proc. Roy. Soc. of N. S. Wales*, 1897.

bar t hangs from knife-edges at C on the upper clip, and is attached at bottom to a short radius arm projecting from the mirror. If the test bar extends, the distance A B increasing by a quantity e, then the upper clip turns on D as a fulcrum and C descends by the amount $(\text{C D}/\text{D A})e = ke$, and the motion transmitted through t rotates the mirror through a corresponding angle. The angular motion of the mirror is measured in the ordinary way by a telescope and scale. Strictly, a scale curved to a circle with centre at the mirror axis should be used; but readings can be taken on a straight scale and a correction applied. Fig. 137 shows one form of the instrument. In this case the adjusting screw for levelling the lower clip acts against the test bar itself, but this throws rather too much strain on the supporting points of the clip. Fig. 139 shows a later instrument, in which the lever at the back of the mirror passes upward against the flat end of the bar t without being attached to it. One advantage of this instrument is that by merely changing the bars s and t it can be adapted to different gauge-lengths on the test bar.

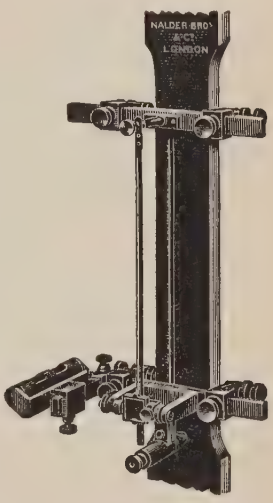


Fig. 137.

In using the instrument on a vertical test bar, after fixing the clips, the lower clip is levelled. Then the vertical scale is placed at the right normal distance (usually six feet) from the axis of the mirror. The zero of the scale is adjusted to be at the same level as the mirror axis,

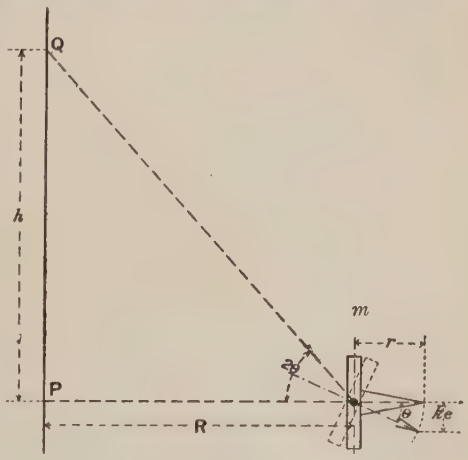


Fig. 138.

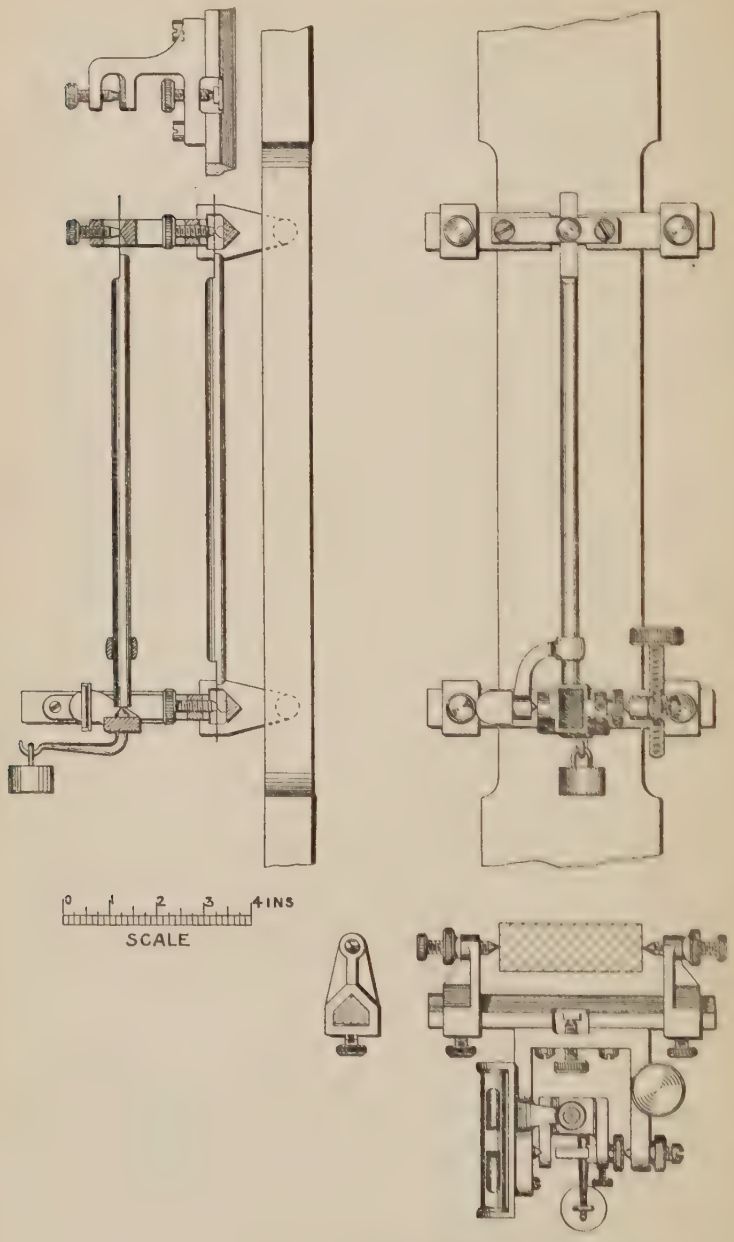


FIG. 139.

and the telescope is placed beside the scale at about the same level. The mirror is now adjusted so as to be nearly vertical, reading some low scale reading, and the scale is moved a little horizontally so that it is seen in the centre of the telescope field.

In fig. 138, let m be the mirror placed vertical, r being the length of the lever arm attached to it. Let P Q be the scale at a distance R from the mirror axis, and let P be the zero of the scale, level with the mirror axis. If now, in consequence of the extension e of the test bar, the lever arm moves through a vertical distance $k\,e$, the mirror turning through the angle θ, then $k\,e = r \sin\theta$, where $k\,e$ is proportional to the extension to be measured. At the same time the line of sight reflected from the mirror moves from m P to m Q through an angle 2θ, and Q is the scale reading in the telescope. The scale reading reckoned from P is $h = \text{R} \tan 2\theta$, and

$$\frac{e}{h} = \frac{r}{k\,\text{R}} \cdot \frac{\sin\theta}{\tan 2\theta}.$$

For small values of θ

$$e' = \frac{r}{k\,\text{R}} \cdot \frac{h}{2} = c\,h$$

is very approximately the value of e, where c is a constant for any fixed values of r, k, and R. It is possible to choose R so that e' is in convenient measure. If e' is first calculated by this simple proportion, the true value e is easily found, for

$$e = 2e' \frac{\sin\theta}{\tan 2\theta}$$

where $2\theta = \tan^{-1} h/\text{R}$. Thus, for a scale divided into centimetres, and R = 6 feet = 182·9 cm., the following table gives the correction:

Scale reading on straight scale in cm. h	R in cm.	$\frac{2\sin\theta}{\tan 2\theta}$	True scale reading on circular scale	Correction for reading on straight scale x
10	182·9	·99922	9·992	− ·008
15	,,	·99758	14·964	·036
20	,,	·99530	19·906	·094
25	,,	·99308	24·827	·173
30	,,	·99027	29·708	·292
40	,,	—	39·300	·700
50	,,	·97325	48·662	1·338
60	,,	·96222	56·733	2·267
70	,,	·94974	66·482	3·518

Let h_1, h_2 be scale readings on a straight scale corresponding to stresses p_1, p_2 on the test bar. Then $h_1 - x_1$ and $h_2 - x_2$ are corrected readings, where x_1, x_2 are the corrections. If C is the ratio of magnification r 2 R k of the instrument, which can be determined directly by a process of calibration, then the true extension e due to the increment $p_2 - p_1$ of stress is

$$e = \text{C}\,\{(h_2 - x_2) - (h_1\, x_1)\},$$

and if l is the gauge-length A B, the coefficent of elasticity is

$$\text{E} = \frac{(p_2 - p_1)\,l}{e}.$$

A curve can be plotted on squared paper in which the abscissæ are scale readings h on a straight scale and the ordinates values of the correction, $x = h\,(1 - 2 \sin\theta / \tan 2\theta)$.

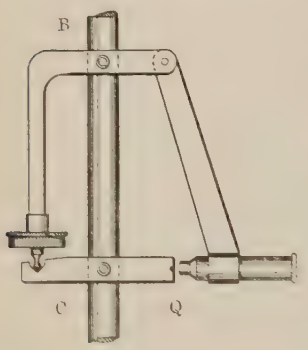


Fig. 140.

147. *Prof. Ewing's Extensometer.*—This instrument is self-contained, and fixed on the test bar by two clips, gripping by pointed screws at four points symmetrical with the axis. The principle is shown in fig. 140. B and C are the two clips on the test bar, each attached by a pair of pointed set screws. Each of these clips has one degree of freedom relatively to the rod—namely, freedom to rotate about the axis of its set screws. A rounded point on B rests in a V-slot cut across C. When the bar extends the point of contact acts as a fulcrum, and the other end of C, viz. Q, moves a distance proportional to the extension of the bar between the clips. The displacement is measured by means of a microscope, which hangs from B and sights a line on Q. In the eye-piece of the microscope is a scale engraved on glass. The object sighted is one side of a fine wire stretched across a hole in a plate at Q, and illuminated by a small mirror behind. To calibrate the instrument there is a micrometer screw and graduated head attached to the rounded point by which B rests on C. By turning this screw through one revolution (pitch $\frac{1}{50}$ of an inch) the object sighted at Q moves $\frac{1}{50}$ of an inch, and this

determines the value of the scale readings. This movement corresponds to 50 divisions of the eye-piece scale as the instrument is constructed. By pulling in or out the eye-piece the instrument can be so adjusted that one rotation of the micrometer screw on B corresponds exactly to a displacement of 50 scale divisions at Q. Hence, one division on the scale corresponds to $\frac{1}{2500}$ of a inch. But the movement of Q is double the extension of the bar, so that one scale division corresponds to $\frac{1}{5000}$ of an inch of extension, and the scale divisions can be subdivided by estimation to tenths. There is a convenient arrangement for holding the clips exactly at 8 inches distance when fixing them on the bar. The instrument is very convenient and rapid in use. The detailed arrangements are described in a paper on the measurement of small strains by Prof. Ewing (*Proc. Roy. Soc.*, 1895).

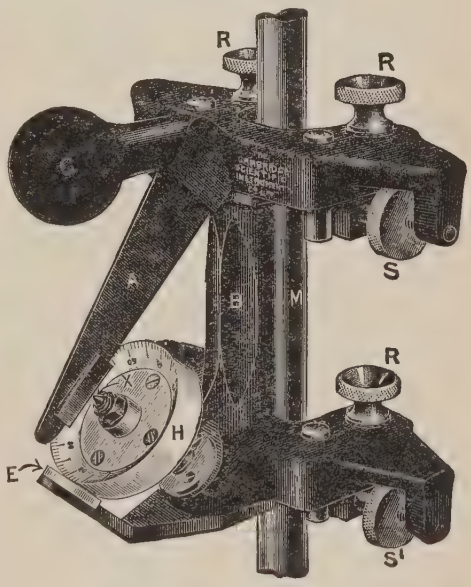


FIG. 141.

148. *The Cambridge Extensometer.*—Fig. 141. A very simple and accurate extensometer is made by the Cambridge Scientific Instrument Company. Two solid clips are attached to the test bar M by points. The steel rods carrying these points move in geometric slides, and after being driven into punch marks in the test bar are clamped by the heads R R. The lower clip carries a micrometer screw H fitted with a hardened steel point X; it also carries a vertical arm B, at the top of which is a steel knife-edge. The clips work together about this knife-edge. A nickel plated flexible steel tongue A forming part of the upper clip is carried over the micrometer point X. The clip and tongue form a lever, with the knife-edge as fulcrum, magnifying the extensions five

times. In use the flexible tongue is vibrated and the micrometer head turned till the point x just touches a steel knife-edge on the tongue. The instrument is suitable for specimens up to $\frac{3}{4}$-inch diameter and 4 ins. or 2 ins. gauge-length. A centring gauge is supplied for fixing the instrument. The National Physical Laboratory reports that the instrument is reliable to about a thousandth of a millimetre.

Fig. 142 shows a marking-off tool, also made by the Cambridge Scientific Instrument Company, for accurately indenting the test bar with the four punch marks required in fixing the extensometer. It consists of a cast-iron base with two V-grooves. The test bar is clamped in another groove at right angles. A centre punch lying in each of

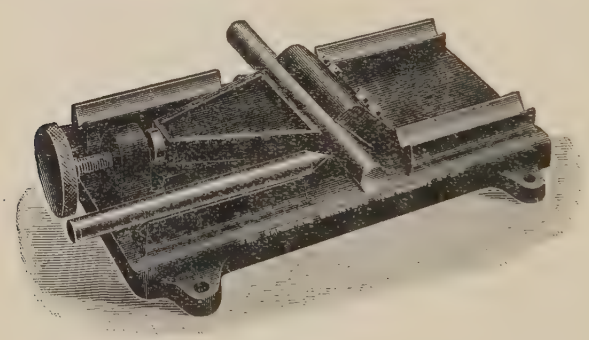


Fig. 142.

the grooves in succession is tapped with a hammer and forms the punch marks.

149. *Instrument for Measuring the Compression of Short Blocks.*—For measuring the compression of short blocks, such as cubes of stone, extremely minute measurement is necessary. The author has employed the arrangement shown in fig. 143, which combines lever and optical magnification, and at the same time gives by a single reading the mean compression of the two sides of the block.

A rectangular frame c_2, c_2, with adjustments for blocks of varying size, is clamped on the base of the stone cube by four pointed set screws. It carries an upright pillar p, with a hardened steel adjustable top, on which rests the

knife-edge of an upper frame c_1, which is clamped on the cube by two set screws near the middle and near the top. The frames are prolonged by the levers l_1, l_2, so that the ends a and i move two and a half times as much as the points of the frames fixed in the cube. The ends of the levers carry silver plates with a fine diamond scratch, and these plates are adjusted to be near together initially by the adjusting screws at p and a. The lever l_2 has a constant position relatively to the plane through the points in the set screws in the frame c_2. The lever l_1, turning on its knife-edge on the pillar p, rises at i two and a half times as much as the stone compresses between the set screws on c_1 and those on c_2. Further, as the instrument is entirely carried by the stone cube, it is not affected by any movement or elasticity of the machine. During the test the distance between the diamond

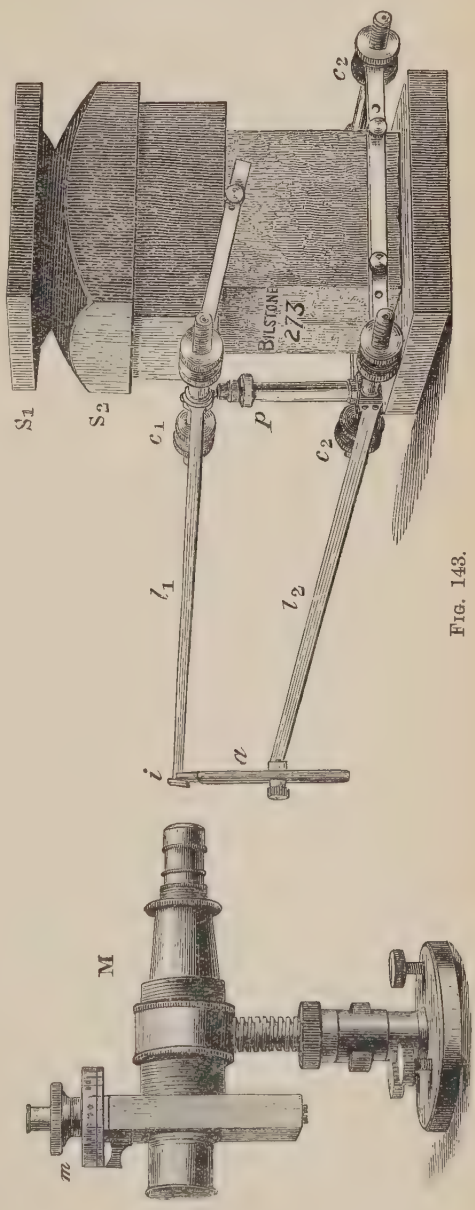


FIG. 143.

scratches on a and i is measured by the microscope M and the micrometer m. Readings to $\frac{1}{20000}$ and $\frac{1}{50000}$ inch can be taken with moderately powerful object glasses. The chief difficulty is to get the diamond scratches fine enough. The fixed cross wire of the micrometer is first set on one diamond scratch, the movable wire on the other. Then the reading of the micrometer head gives the distance.

150. *Torsion Micrometer.* — For observing the large plastic-deformation by torsion, which for mild steel may amount to several times 360°, it is sufficient to have a circle on the straining torsion head divided into degrees. The other head does not sensibly move, and the deformation of the ends of the bar in the holding nuts is not very serious. But for measuring the elastic deformation very

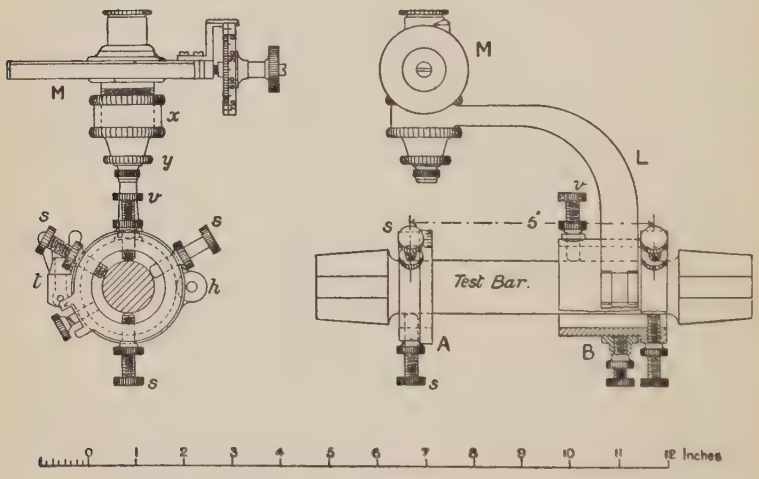


Fig. 144.

accurate means of measurement are necessary, and the instrument must be independently fixed on the bar itself. A torsion test is the best means of determining the coefficient of rigidity C.

The author has used an instrument for measuring elastic distortion shown in fig. 144. Two rings, A and B, are clipped concentrically on the torsion test bar, by three set screws. One of these, A, has an arc finely divided on silver into degrees and quarter degrees. The other, B, carries on

a projecting arm a microscope micrometer M. The set screw v merely steadies the arm. The microscope is initially set on the arm so that, when the scale is in focus, the micrometer screw carrying the cross wires moves the wires over half a degree for one rotation. The divided head of the micrometer screw has 100 divisions, so that the micrometer reads to $\frac{1}{200}$ of a degree. In use the micrometer measures the distance from the nearest division of the scale on the ring B.

151. *Measurement of Deflection in Transverse Tests.*—The

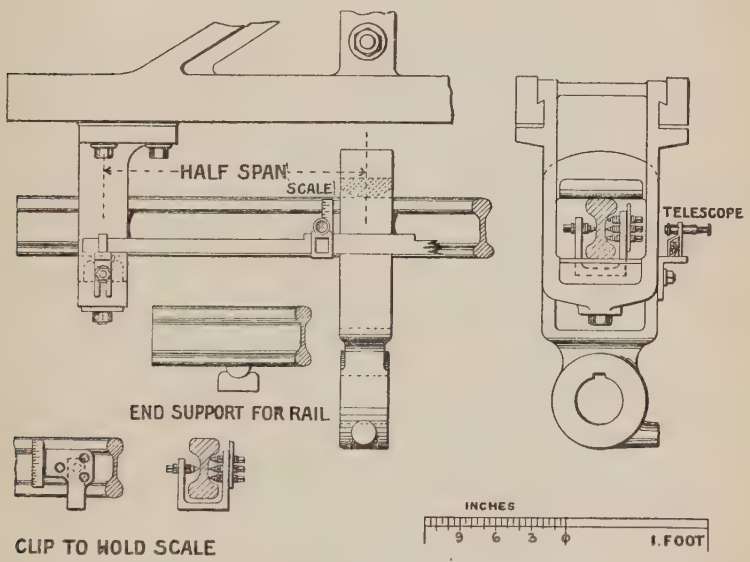


FIG. 145.

author has used the arrangement shown in fig. 145. A finely divided scale is fixed at or very close to the centre of the rail or other bar subjected to test. The clip which holds this scale has a set of three pinching screws on one side and one on the other. The scale cannot therefore rotate relatively to the bar. A light wood bar resting on the supporting shackles carries a telescope with a cross wire in the eye-piece.

152. *Instrument for Calibrating Extensometers.*—Fig. 146 shows an instrument which the author has found useful in

calibrating extensometers and other work of a similar kind. It can be used vertically or horizontally. It consists of a stand A and a sliding piece B. The slide is V-shaped and

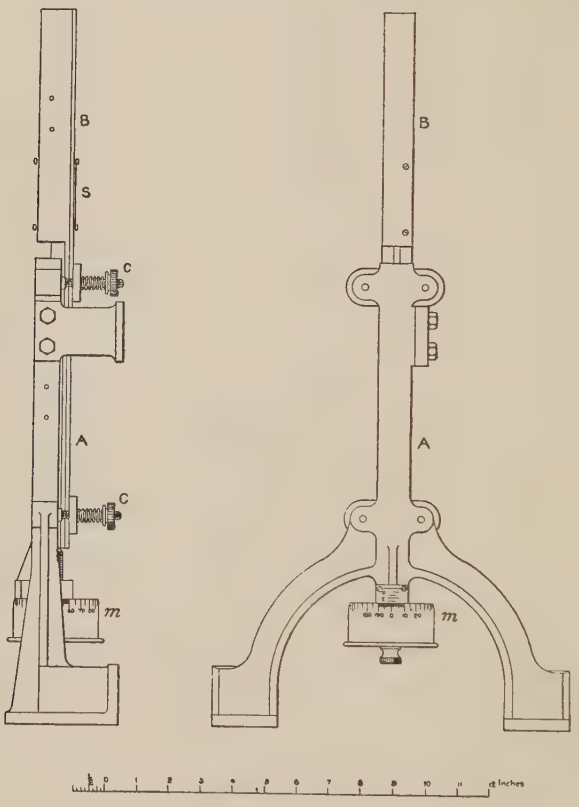


FIG. 146.

B is held to the slide by light spring clips C, C. Fixed in the stand A and driving the sliding piece B is a micrometer screw, the head of which is seen at *m*. The pitch of the screw is $\frac{1}{50}$ inch and the head is divided into 200, so that the direct reading (apart from estimation) is $\frac{1}{10000}$ inch. The extensometer can be fixed with one clip on A and the other on B. Then the micrometer reading and extensometer readings can be compared. For better comparison a scale divided into $\frac{1}{200}$ of an inch is fixed on B, and this can be

observed through a microscope. The scale can either be used in calibrating the micrometer screw of the instrument or directly in determining the value of the extensometer readings. The extensometer being on the instrument, the micrometer screw is turned so that $\frac{1}{200}$ inch at a time is observed in the microscope reading the scale. Then the corresponding extensometer reading is taken.

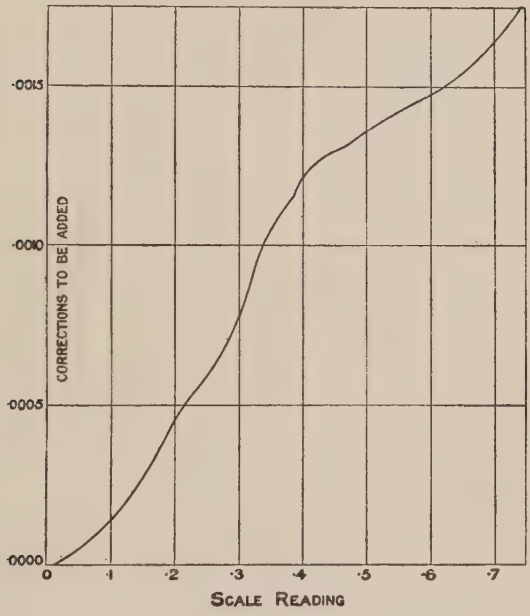


FIG. 147.

Interference Method of Calibrating Extensometers.—Messrs. Morrow & Watkin have described an interference method of calibrating extensometers. The extensometer is fixed on two cylinders having a gap between them. The gap can be varied by a lever actuating a screw. The amount of alteration is measured (1) by observations of the interference rings formed in an optical apparatus in the gap and (2) by the extensometer itself. The points to be examined are (1) the magnification constant, (2) the lost time when starting or stopping the motion of the cylinders, and (3)

the proportionality of the extensometer readings to the displacement.

153. *Calibrating Micrometer Screws.*—No micrometer screw should be trusted for accurate measurement unless it has been calibrated. Generally the most accurate standard of reference is a finely divided scale graduated on some trustworthy dividing machine. A scale with an inch divided into 200ths is convenient. Such a scale may be arranged to slide and to be driven by the micrometer screw to be tested. A microscope with cross wire is placed so as to have graduations in focus. If then the scale is moved division by division, and at each a reading on the graduated head of the micrometer screw is taken, the errors of the screw relatively to the scale are found. The most convenient way of making such a calibration available for correcting the screw readings is to plot a curve of errors on squared paper. Fig. 147 is a sketch of such a curve.

The abscissæ are readings on the micrometer screw. The ordinates are the corresponding corrections or differences from the scale reading. The error between any two readings on the micrometer screw is the vertical intercept between two points on the curve corresponding to the readings.

154. *Comparison of Different Extensometers.*—The author was of opinion that the calibration of extensometers in use for measuring elastic strains was not very satisfactory, and that differences given for elastic constants were due to instrumental errors rather than to differences in the properties of the material. At his instance a committee of the British Association undertook an investigation of the variations of measurement with different observers and instruments using the same test bars.[1] Two sets of three test bars were prepared, one in each set being a flat bar $2'' \times \frac{1}{2}''$ in section, one a round bar $1\frac{1}{4}''$ in diameter, and one a round bar $\frac{3}{4}''$ in diameter. These bars were sent to several observers, who were good enough to make careful measurements of the extensions within the elastic limit with different measuring instruments. The following table gives the values of E obtained from these measurements:

[1] 'Calibration of Instruments used in Engineering Laboratories.' Report of a committee of Section G, *British Association Reports*, 1895, 1896, and 1897. It may be stated that extensometers are more accurate now than they were in 1897.

VALUES OF COEFFICIENT OF ELASTICITY OBTAINED BY DIFFERENT OBSERVERS. (TONS PER SQ. IN.)

Bar	Observer	Results by each observer	Mean results by each observer	Mean of all results on one bar	Mean of all results on bars of same material and size
E	J. A. Ewing	13290	13290		
		13290			
	H. S. Hele Shaw	13116	13138		
		13160			
	W. C. Unwin	13198	13214	13225	
		13231			
	D. S. Capper	13260	13260		
		13260			
		13200			
		13320			
		13260			
		13260			13249
	A. B. W. Kennedy	13430	13465		
		13430			
		13500			
		13500			
F	T. Hudson Beare	13050	13105	13273	
		13150			
		13070			
		13150			
	J. Goodman	13250	13250		
		13250			
	J. A. Ewing	13380	13365		
		13350			
	H. S. Hele Shaw	13310	13191	13274	
		13072			
K	W. C. Unwin	13495	13440		
		13385			
	D. S. Capper	13100	13100		
		13040			
		13100			
		13160			13245
	A. B. W. Kennedy	13200	13200		
		13200			
	T. Hudson Beare	13260	13262		
		13420			
		13210			
		13160		13215	
L	J. Goodman	13244	13244		
		13244			
	D. S. Capper	13120	13153		
		13120			
		13210			
		13210			
		13130			
		13130			

VALUES OF COEFFICIENT OF ELASTICITY OBTAINED BY DIFFERENT OBSERVERS. (TONS PER SQ. IN.)—*continued*

Bar	Observer	Results by each observer	Mean results by each observer	Mean of all results on one bar	Mean of all results on bars of same material and size
A	A. B. W. Kennedy	13100 13200	13150	13182	13193
	T. Hudson Beare	13160 13260	13210		
	J. Goodman	13110 13110	13110		
	D. S. Capper	13260 13260	13260		
	J. A. Ewing	13260 13310	13285		
B	H. S. Hele Shaw	13180 13060	13120	13203	
	W. C. Unwin	13294 13302	13298		
	D. S. Capper	13110 13110	13110		

The foregoing table contains all the values of E, calculated from the total range of stress to which the bars were subjected. The total range of stress in each case was about the maximum range which could safely be used without risk of straining the bar beyond its elastic limit.

Bars E, F, K, L were all cut from the same rolled bar, and of these E and F were approximately of 1·25 inch diameter and K L 0·75 inch diameter. Bars A and B were cut from the same plate, and were approximately of the section $2 \times \frac{1}{2}$ inches.

If the mean value of E for each steel, from all the determinations of all the observers, is taken as a standard, then there are deviations in the determination of E by individual observers which amount in one case to 2 per cent. of the mean, and in several cases to 1 per cent.

CHAPTER X

AUTOGRAPHIC RECORDING APPARATUS

All ordinary testing is largely concerned with the determination of the relation of stress and strain at different loads. It has been shown that the relation of stress and strain throughout a test can be graphically exhibited by a stress-strain diagram. If a testing-machine could be made itself to describe a stress-strain diagram, it would be an interesting record of the behaviour of the test bar.[1] Such a diagram would show the yield point, if there was one, the maximum load and breaking load, and the elongation at each period of the test. From sufficiently detailed measurements during the test such a diagram can be plotted. But such plotting is laborious, and it is very convenient to have it done mechanically. Further, an autographic diagram is free from personal bias and accidental errors of record.

155. *Thurston's Autographic Testing-machine.*[2] — This machine is intended to test the quality of materials by means of inferences from the torsional strength and rigidity. Tests of that kind are convenient because the specimens do not require to be large, and the twisting moments necessary can be produced by comparatively small forces at a moderate leverage. The deformation before fracture is also large and easily measurable. Inferences from torsional experiments, however, are hardly so trustworthy as those from direct stresses, except in the case where a material is intended to be used to resist twisting. The test bar for this machine is a small cylindrical bar $\frac{1}{2}$ inch to $\frac{5}{8}$ inch in diameter, with square ends. It is placed in a pair of jaws, one connected with a

[1] Much of the information in this chapter was given in a lecture on 'The Employment of Autographic Records in Testing,' at the Society of Arts, February 1886.

[2] This machine has been very often figured and described. Professor Thurston's papers will be found chiefly in the *Trans. Am. Soc. of Civil Engineers*, and the following may be referred to: 'The Mechanical Properties of Materials of Construction,' 1874, vol. ii. p. 349; vol. iii. p. 1.

heavily weighted pendulum, the other with a worm and wheel. By driving the screw-gearing, one end of the specimen is rotated, and the twisting moment is balanced by the weighted pendulum acting at the other end, and is measured by the sine of the angle through which the pendulum is moved.

A drum covered with a sheet of specially ruled section paper is fixed to the worm-wheel shackle, and a pencil attached to the pendulum turns with it. Hence the pencil traces on the drum a circumferential line proportional to the difference of motion at the two ends, or to the twist of the specimen. The pencil has another movement parallel to the axis of the test bar; as it rotates with the pendulum, it is forced by a guide curve to move a distance axially proportional to the twisting moment (sine of angle of inclination of pendulum). Hence, the pencil draws a stress-strain curve, the abscissæ of which are the strains or angles of twist and the ordinates the twisting moments. But the machine has defects. It is wrong in principle to take the register of the strains from the clips which hold the specimen. The arrangements do not secure perfectly that there is no longitudinal or bending stress. The friction of the pendulum journal and the momentum of the pendulum may both influence the results.

156. *The Polmeyer Autographic Apparatus.*—In 1882 the author saw at Dortmund a 50-ton tension testing-machine, designed by Professor Polmeyer for autographic testing. It is a pendulum machine, with a very long pendulum having a ton weight at the end. As one end of the specimen is pulled by a hydraulic press, the other pulls on the pendulum, and the stress is related to the angular rise of the pendulum. It is easy to see that a paper connected by one wire to the pendulum, and a pencil connected by another wire to the specimen, can be so arranged as to draw a true autographic diagram.

157. *Machines with Automatic Adjustment.*—In some American machines autographic apparatus is attached, and there is in addition an electric arrangement by which the position of the poise weight is automatically adjusted to keep the lever floating.

As the steelyard rises or falls against its stops it completes an electric circuit, which starts an electro-motor, which moves the poise. Thus, if the lever rises, showing

that the stress exceeds the load applied by the steelyard, the electro-motor moves outwards the counterpoise till, balance being restored, the circuit is broken. Geared to the arrangements for moving the counterpoise is a drum or cylinder on which the record is made, and the rotation of this drum is therefore exactly proportional to the movement of the counterpoise on the steelyard. Consequently, a pencil held fixed over the drum would trace a circumferential line the length of which is proportional to the load on the specimen.

The pencil, however, has a second motion parallel to the axis of the cylinder, derived from a thin flexible steel tape attached to two clips on the specimen. This is led over pulleys, so as to move the pencil axially along the cylinder. The defect of the arrangement is that the elongation is not magnified, and the tape is so long that it is hardly possible it can give the pencil a quite true movement free from any error due to slack in the tape.

158. *Mr. Wicksteed's Autographic Apparatus.*—This is an apparatus fitted to the Buckton testing-machine, shown in fig. 77, p. 145. The motion of the pencil which indicates the load is derived from the fluid pressure in the hydraulic press, and not from the weighing apparatus. A pipe from the hydraulic press F is led to a small cylinder, with a piston of 1 sq. in. in area. This piston is controlled by a strong spring, 15 inches long when unloaded, 5 inches long when loaded with 22 cwt., the full pressure on the piston when the pull of the machine is 50 tons. During a test, as the pull and consequently the fluid pressure increases, the spring is compressed, and the pencil P moves horizontally along the recording drum D. On the test bar *s* are two clips J J, and a wire attached to weights resting on the lower clip is carried over a pulley on the upper clip, and over the links G, finally serving to rotate the recording drum D by an amount proportional to the elongation. Hence, the pencil having an axial motion proportional to the load, and the drum a motion of rotation proportional to the extension, a stress-strain diagram is described.

To eliminate the influence of the friction of the small indicator piston, it is kept in rotation by the pulleys shown at the end of the recording apparatus. Practically the friction of the cup leather of the small piston is neutralised by this rotation. The object of the link-work G is to eliminate the influence of the motion of the test bar as a whole, due to the

sway of the lever or slipping in the clips. The arrangement is correct in principle. There is some practical convenience in taking the load indication from the hydraulic press instead of the weighing apparatus. The pressure in the hydraulic press is chiefly due to the tension of the specimen, but a part of it is due to the unbalanced part of the counter-weight, to the friction and inertia of the crosshead and slides, and to the cup-leather friction of the main ram. The diagram can only have a uniform scale so far as these additional pressures are proportional to the load on the specimen. Mr. Wicksteed determines the scale of the diagrams by occasionally checking them by the use of the lever. He has also found that for the small diagrams taken the scale is practically uniform if the ram is kept moving in one direction.

159. *The Author's Autographic Apparatus.* — In 1882, when selecting a testing-machine for Cooper's Hill College, the author perceived that Mr. Wicksteed's type of testing-machine, with a single jockey-weight, moved by a screw, lent itself very conveniently to the application of autographic apparatus, and of autographic apparatus of a very simple kind, which would not interfere with the ordinary operations of testing.

In the Buckton testing-machine the stress is weighed by a steelyard, on which there is a travelling jockey-weight, driven by a screw; consequently, the rotations of the screw are exactly proportional to the movement of the weight, and to the stress on the specimen. It is from this screw that a vertical paper cylinder d (fig. 148) is driven. A small catgut belt drives a worm, acting on a worm-wheel of 200 teeth, on the paper cylinder. As the resistance of the paper cylinder is very small, the motion given by the belt is quite accurate, and it has this convenience, that by means of a stepped pulley a several scales are available for the diagram. Necessarily, the specimens vary in size and strength, and it is extremely convenient to enlarge the load scale of the diagram for small specimens, and diminish it for large ones. The pencil p slides on guides parallel to the axis of the paper, and it is connected to the specimen by a very fine wire w, kept strained by a counter-weight e. The wire is so fine that a counter-weight of 2 or 3 ounces is quite sufficient to keep it taut and overcome the friction of the slides.

On the specimen s are two clips $c\,c$, the construction of which is so arranged that they are rigid in position on the

bar, and which define exactly the length in which the elongation is taken, and do not become slack as the bar contracts.

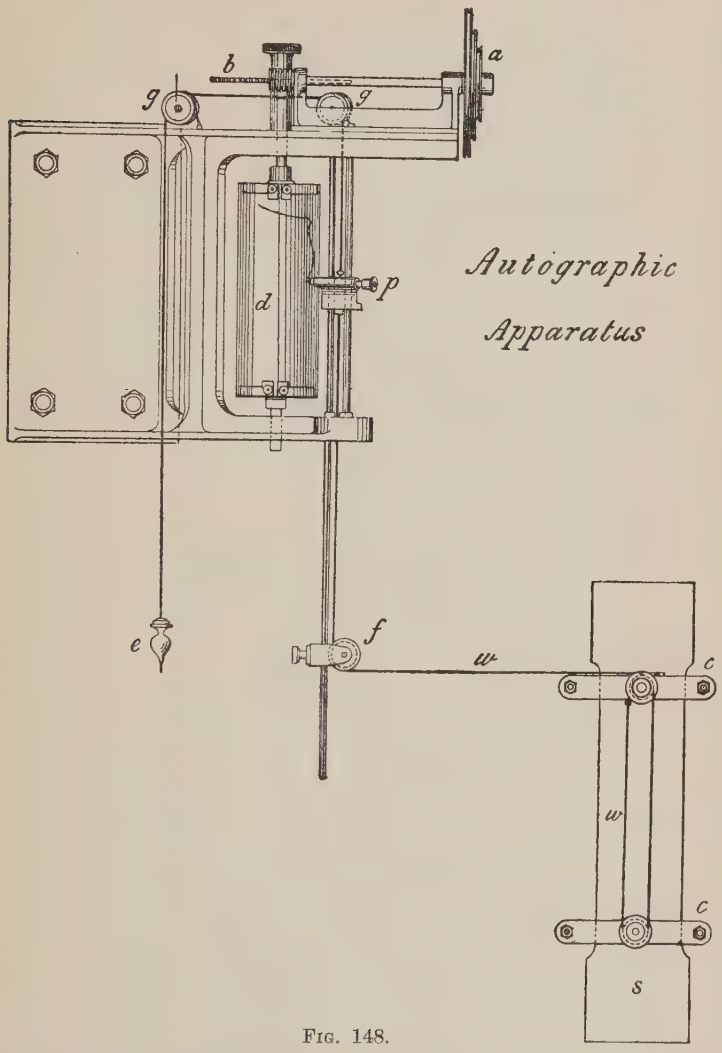


Fig. 148.

It is extremely convenient to magnify more or less the elongation, so as to get a larger diagram. The thin wire is attached to the top clip, taken over a pulley on the bottom clip, again over a pulley on the top clip, and then horizontally

to the guide pulley *f* on the autographic apparatus. In this way the extension is exactly doubled.

By properly placing the apparatus, and leading off the wire from the specimen parallel to the knife-edge of the testing-machine, no measurable error is introduced due to motions of the specimen. Parallel to the knife-edge the specimen has no motion. It has a small vertical motion, due

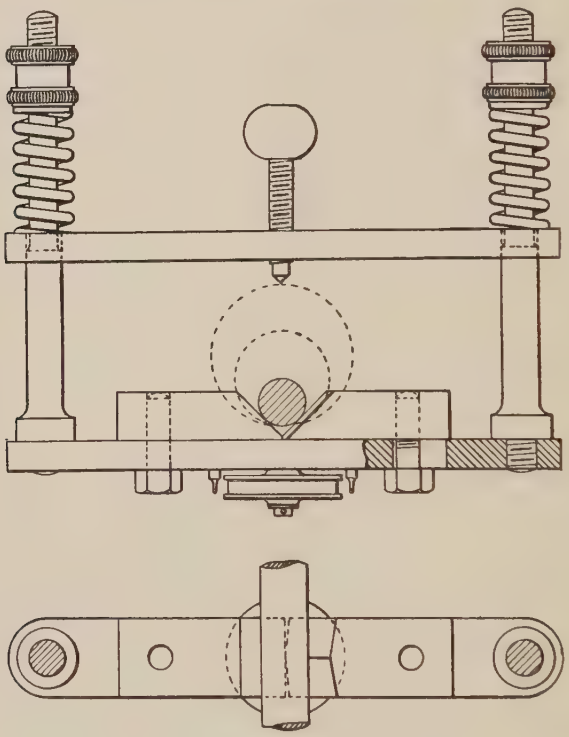


Fig. 149.

to variation of position of lever, slipping in clips, &c. But the greatest possible motion of this kind would not introduce an error in the diagram of $\frac{1}{100}$ inch.

160. *Test Bar Clips for Autographic Apparatus.*—The movement of the pencil which records extension is almost necessarily derived from clips attached to the test bar. For accuracy, these clips must satisfy these conditions: (*a*) They must grip the bar without any possibility of slipping or

canting. (*b*) They must be so fixed that the extension recorded is that of a known exact gauge-length. (*c*) They must close on the bar as it contracts laterally with increase of stress. Fig. 149 shows a clip used by the author for cylindrical bars. There are two flat bars which tend to close under the action of spiral springs compressed by adjusting nuts. One

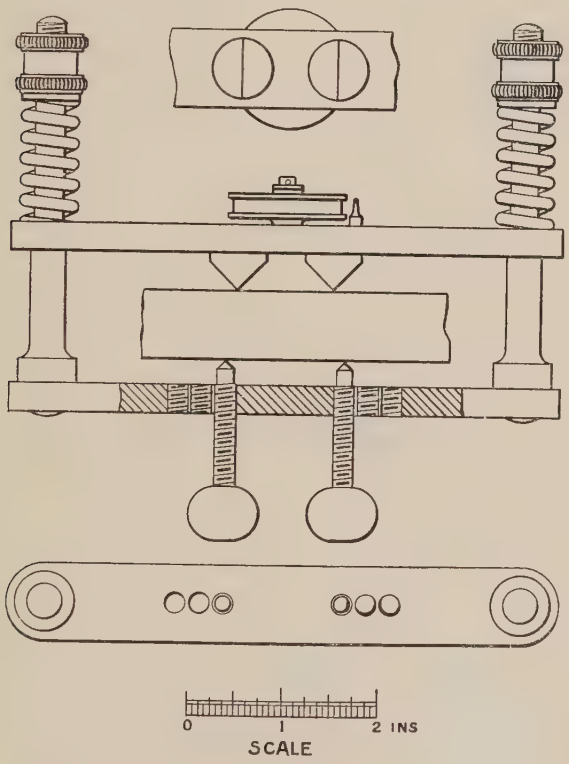


Fig. 150.

bar carries a pointed set screw, the other a block with a V-groove formed so as to have a plane surface on one side and a knife-edge on the other. The bar is then held with regulated pressure between a point, a line, and a plane, and the clip can neither slip nor cant. The gauge-length is the distance between the set screws of two such clips. The pulley for the wire transmitting the record of extension is on one of the bars.

Fig. 150 shows a somewhat similar clip for flat plates. The test bar is held between two pointed set screws on one side and two smooth knife-edges on the other. The set screws define the gauge-length.

161. *Portable Recorder for Tension Tests.*—Mr. G. C. Henning has described[1] an arrangement of recording drum which can be fixed directly on the bar. The drum is carried by one of two clips fixed on the test bar. A lever arrangement somewhat like that of a steam-engine indicator carries a pencil which records extension on the drum. The drum is rotated by a string connected with the travelling jockey-weight which balances the stress in the bar.

162. *Electric Semi-automatic Recording Apparatus.*—All the ordinary forms of autographic apparatus fail to register in any useful way the small strains within the elastic limit. A lever arrangement has been tried to magnify the extensions, but with a great magnification the difficulty and error introduced render the arrangement worthless. It occurred to the author that a totally different method of registration would in some cases be very convenient. A large recording drum is connected with the screw of the jockey-weight, so as to turn circumferentially a distance accurately proportional to the load on the specimen. A pencil moves on a slide parallel to the axis of the cylinder. To give motion to the pencil there is an arrangement of electro-magnets and ratchet wheels. With a commutator in hand the observer can send a signal which makes the pencil move a step forwards or backwards at any moment.

Now, suppose a test proceeding, and that by the telescope mirror and scale the extensions are being observed. If a signal is sent at each increase of extension of, say, $\frac{1}{10000}$ inch, a stepped figure will be obtained, from which the extension at any moment and the corresponding load can easily be read off. And the record in this way is effected with great ease and rapidity.

Fig. 151 shows one of the diagrams obtained, and contains a record of more than 150 extensions, taken in less than half an hour. Half the readings are taken with an increasing load, the other half while the load was being removed. The figure is about one-fourth the actual size of the diagram, and the steps correspond to $\frac{1}{5000}$ inch of extension. The

[1] *Trans. Am. Soc. Mech. Eng.*, vol. xviii. 1897.

diagram is one of the first taken in this way by students at the Central Technical College. It is not a particularly perfect diagram, but it illustrates the kind of record obtained by this method.

163. *Professor Kennedy's Autographic Apparatus.*—An apparatus devised by Professor Kennedy and Professor

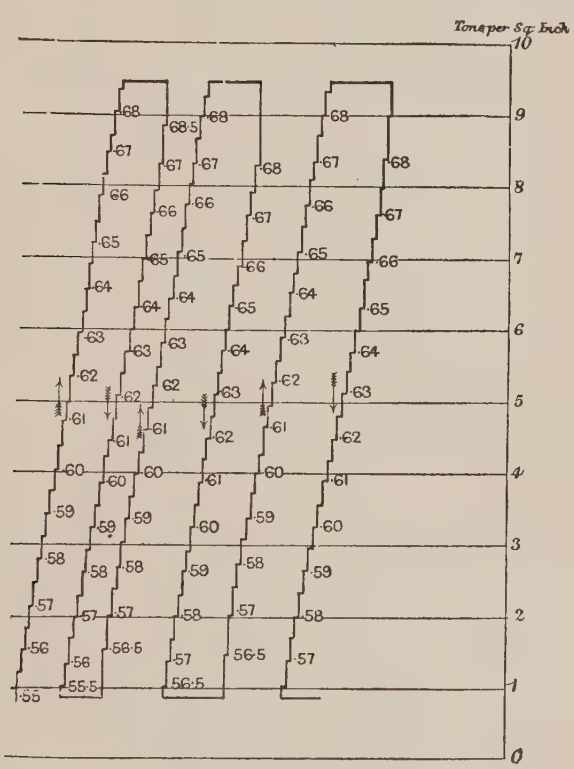


Fig. 151.

A. G. Ashcroft is of a different kind. The following description is taken from Professor Kennedy's paper:[1]—'The apparatus cannot be said to be suitable for general use, but for a laboratory, where it is in skilled hands, and not subject to rough usage, Professor Kennedy believes it to give more trustworthy diagrams than any of the other forms just devised.

[1] *Proc. Inst. of Civil Engineers*, vol. lxxxvii. p. 30. A detailed drawing of the apparatus is given.

It has also the advantage that it is wholly independent of either the poise or the ram, or even any part of the framing of the testing-machine, and that its own parts are so light that the diagram may be assumed to be free from any errors due to inertia. The test piece *a* (fig. 152) is placed in the machine *in series* with a stronger bar *b*, called a spring piece, and the two, which are connected directly by a simple coupling, are pulled simultaneously, the one through the other. The spring piece is of such a material that its limit of elasticity occurs only at a load greater than that which will break the test piece. It must also be of material ascertained by previous experiment to be perfectly elastic, so that its extension is strictly proportional to the pull on it, and therefore to the pull on the test bar. By a simple arrangement a very light pointer *c* is made to swing about an axis through an angle proportional to the extension of the spring

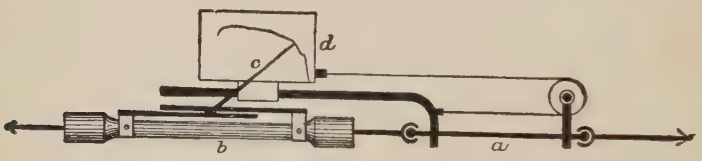


FIG. 152.

piece, and proportional, therefore, to the pull on the test bar. The end of this pointer touches a sheet of smoked glass *d*, to which is given a travel in its own plane, proportional to the extension of the test piece, and in this way the diagram is drawn. After the experiment the glass is varnished to fix the black, the necessary particulars are written on it with a scribing point, and the whole is used as a negative and multiplied by photography.'

164. *Autographic Extensometers, recording Time and Extension.*—Many attempts have been made to study experimentally the action of a travelling load on a structure such as a bridge. In such cases the train which forms the travelling load moves with uniform speed across the structure, each member of which passes through a cycle of changes of stress related to the position of the moving load. If a diagram can be drawn with the strains (extensions or compressions) as ordinates and the time as abscissæ, it is possible to infer the stresses corresponding to each position of the moving load. The first

instrument of this kind was designed by Dr. W. Frankel, and constructed by Oscar Leuner in Dresden.[1]

Fig. 153 is a diagram of the instrument. Two clips, c_1, c_2, are attached to the member of the structure the strain of which is to be recorded. Between these is the tubular link attached to the clips c_1 at b, and acting at the other end

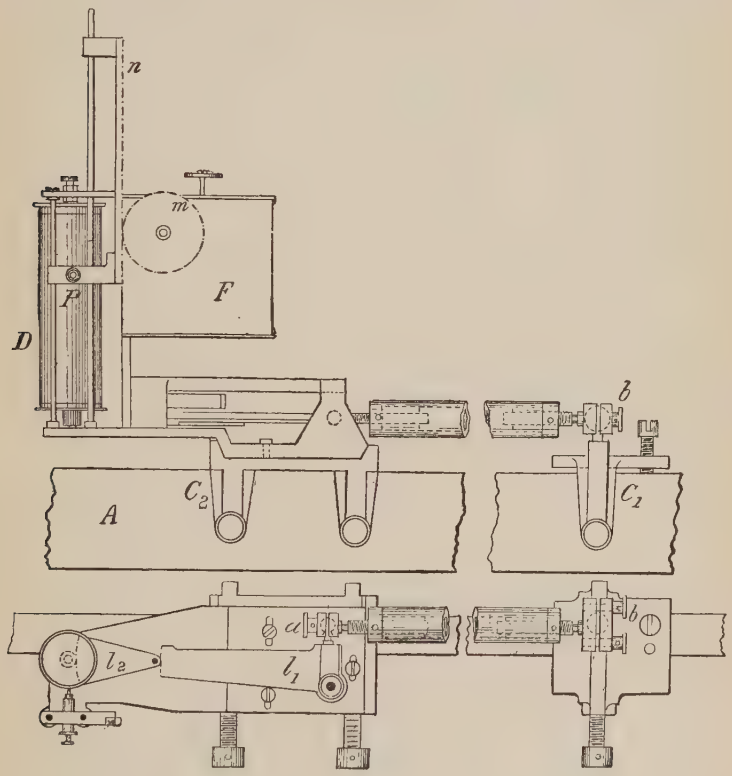


Fig. 153.

a on the unequal-armed lever l_1. The lever l_1 is toothed at the edge, and drives the lever l_2, and this, in turn, gears with a small pinion on the spindle of the drum D. The levers form a spur-wheel train magnifying the extension 200 times, and the drum D moves under the pencil P a distance proportional to the strain. The clock F at the same time moves the pencil axially at a uniform speed, driving the pinion m and

[1] *Civilingenieur*, 1881, vol. xxvii. § 250.

rack *n*. Consequently, a diagram is obtained with abscissæ proportional to the time and ordinates proportional to the strain.

The most ingenious mechanical contrivance in Dr. Frankel's instrument is that by which loss of time, or backlash, in the spur-wheel multiplying gear, is prevented. Each toothed driver consists of two parts, connected by a spring only, which presses one part forwards and the other backwards against the two faces of contiguous teeth of the driven wheel. There is always contact, therefore, between driving and driven teeth for motion in both directions, and any motion in either direction is communicated instantly and without loss of time.

165. *Autographic Deflectometer of Askenasy.*—This is a small apparatus for drawing the deflection curve of a beam during the passage of a load over it. A paper recording-drum, moved by clockwork, is clamped on a beam or bridge. An independently supported style traces a curve on the drum. The style is on a vertical rod, at any point of which it can be fixed, and this can be clamped to a wooden beam supported independently of the deflecting beam. The curve has time abscissæ and deflection ordinates.

CHAPTER XI

PROCEDURE IN ORDINARY TESTING

166. *Selection and Preparation of Test Bars.*—In the selection, cutting out, and preparation of test pieces, it is important to subject them to no treatment likely to alter their properties. The test of a material exactly in its manufactured condition is what is usually required. But special tests may, in addition, have to be made to determine the effect of annealing, tempering, &c. In rails, axles, tyres, &c., pieces for tensile or torsion or bending tests must be cut out of the finished piece by cold sawing or planing. In the case of plates, pieces are removed by shearing, but bending of the piece should be prevented as far as possible, and the sheared edges removed by a cutting tool before testing. In large forgings test bars should be cut from the centre of massive portions of the forgings. If a forging has been drawn out in one direction it is desirable to cut two test bars, one in that direction, and one at right angles to it. Iron plates are generally tested in the direction of rolling and across it. For testing the metal used for castings, some special test bars may be cast with metal taken at about the middle of each operation. In many cases a piece may be cast on a casting and cut off afterwards for testing.

Bending, hammering, or heating pieces to be used for testing should be avoided. They should be prepared by turning, planing, or milling, and rough edges removed by a file. If a piece must be straightened, as, for instance, when cut from a pipe, it is generally best to heat it, but only to the lowest temperature at which it can safely be treated (dull red at most). Some materials are tested in three conditions: (*a*) normal, or as received; (*b*) tempered, or oil hardened; (*c*) annealed. In annealing the bar should be in a closed gas or petroleum furnace, and it is well to cover it with quicklime, which prevents oxidation. In ordinary temper tests,

the piece is heated to cherry red and plunged in water at about 80°.

167. *Proportions of Test Bars for Tension Tests.*—Specifications for constructive materials defining the quality to be supplied almost always contain test conditions. In the case of steel careful testing is of great importance, because its mechanical properties vary through a wide range and small differences in composition or thermal treatment result in considerable variation in its suitability for construction. It is of much importance that tests made at different times and places on material of different origin should be of such a kind that the results are uniform and their interpretation clear and unambiguous. It is misleading if tenacity or elongation on one test sheet has a different meaning from the same data on another test sheet. Now the great care and skill which has been expended on the construction of testing-machines for metals has secured this, that tests can be quite satisfactorily made and that the results so far as the strength of the material is concerned are accurate within a small margin of error. But there is another quality equally important to the engineer, the ductility of the material, generally assumed to be indicated by the elongation of a test bar when broken. Exact limits of percentage of elongation are laid down in specifications. But hitherto the conditions required to ensure that the measure of elongation in one test should be comparable with that in another, have been unsatisfactorily observed.

The law of similarity stated in the chapter on Elongation shows that, for material of given quality, the percentage of elongation in tensile tests is only the same, if the test bars are of geometrically similar form. But it has been common in this country to take a fixed gauge-length of 8 or 10 inches, and to make the transverse dimensions of any size convenient. The elongations in such tests are not comparable.

The French Commissioners recommended that the standard relation between the gauge-length l and the cross-section of a test bar ω should be—

$$l = \sqrt{(66{\cdot}6\,\omega)} = 8{\cdot}16\sqrt{\omega}.$$

A round bar with 200 mm. (7·87 ins.) gauge-length would have a diameter of 27·64 mm. (1·09 in.) and an area of 600 (0·93 sq. in.) sq. mm. They recommended that, as far as practicable, the gauge-length should be varied in accordance

with this relation. The German International Union recommended the relation—

$$l = 11{\cdot}3\sqrt{\omega}.$$

There are very great difficulties, however, in adopting a vary-

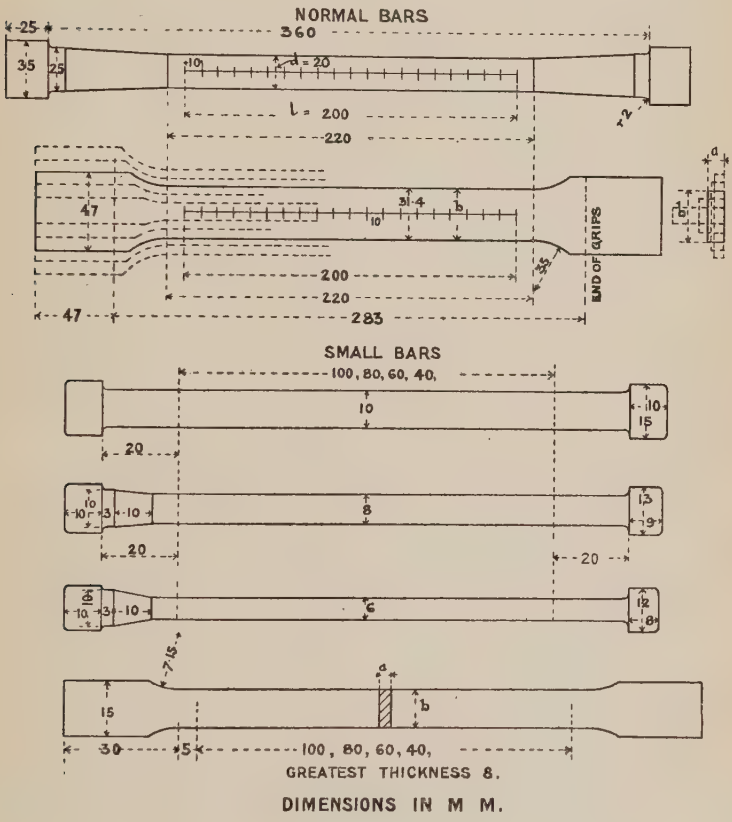


Fig. 154.

ing gauge-length for different cross-sections, or a fixed gauge-length and cross-sections varying in accordance with the formula, because it increases seriously the cost of preparing the test bars.

Fig. 154 gives a diagram of a series of type forms recommended by the Versuchsanstalt at Berlin. The two

upper figures are the standard forms for ordinary round and flat bars, the lower figures the types for bars, unavoidably of special small size.

168. *Test Bars prescribed by the British Standards Committee.*—In this country no system has been generally adopted hitherto. For plates, which form the great bulk of material to be tested, a gauge-length was generally specified, sometimes 8 inches and sometimes 10 inches. The shorter gauge-length was preferred as involving less waste of material. The influence of area of section on the percentage of elongation was wholly disregarded, and usually all plate test bars were machined to a uniform width, to save trouble in adjusting the milling machine heads. For sectional material and for forgings different gauge-lengths and areas were specified in different specifications.

The Standards Committee have made an attempt to systematise testing so that the results on test sheets should have a definite interpretation, without going so far as to hamper and delay the operations of the steel maker; and the manufacturers on the Committee cordially accepted, after some discussion, the arrangements proposed.

In the case of the turned test bars of forgings, it was possible to standardise dimensions which very approximately satisfy the law of similarity. Three sizes of test bars C, D, E (fig. 155) have been selected by the Committee, which are so nearly geometrically similar that for a given material they give practically identical elongations. The forms of the ends for gripping are not prescribed. The gauge-lengths are 2 inches, 3 inches, and $3\frac{1}{2}$ inches, and the corresponding areas are $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ square inch. That is approximately $l = 4\sqrt{\omega}$. Hence, when any one of these standard test pieces is adopted, the percentage of elongation will be comparable with that obtained with any one of the others.

For cylindrical bars—for instance, bars of rivet steel—it was possible to make the gauge-length either eight or four times the diameter, B or F (fig. 155), and to give a rule for the difference of elongation according as one or the other was chosen. These proportions correspond nearly to $l = 9\sqrt{\omega}$ and $l = 4{\cdot}5\sqrt{\omega}$. In that case also the percentage of elongation in bars of different sizes is strictly comparable. The rule is that the gauge-length shall not be less than 8 or 4 diameters. It is convenient and sufficient if the length is, to the nearest half-inch, in accordance with the rule.

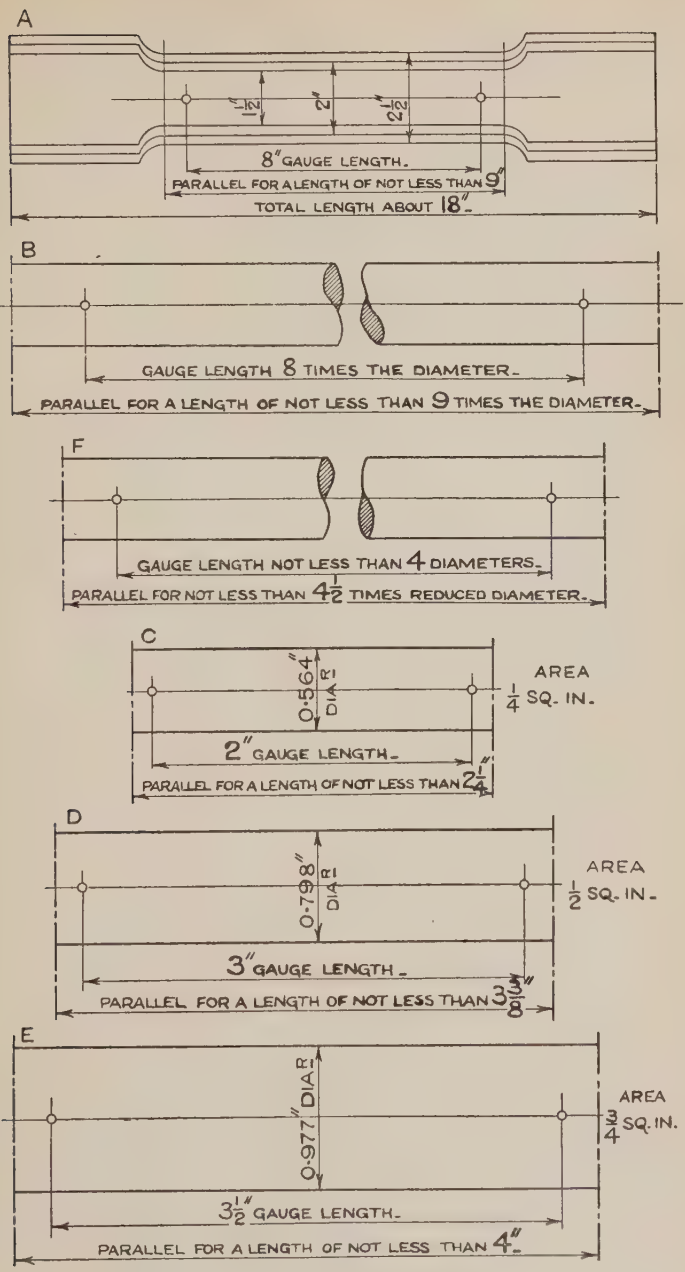

A
½"
2"
½"
8" GAUGE LENGTH.
PARALLEL FOR A LENGTH OF NOT LESS THAN 9"
TOTAL LENGTH ABOUT 18".
B
GAUGE LENGTH 8 TIMES THE DIAMETER.
PARALLEL FOR A LENGTH OF NOT LESS THAN 9 TIMES THE DIAMETER.
F
GAUGE LENGTH NOT LESS THAN 4 DIAMETERS.
PARALLEL FOR NOT LESS THAN 4½ TIMES REDUCED DIAMETER.
C
0·564" DIAR.
AREA ¼ SQ. IN.
2" GAUGE LENGTH.
PARALLEL FOR A LENGTH OF NOT LESS THAN 2¼"
D
0·798" DIAR.
AREA ½ SQ. IN.
3" GAUGE LENGTH.
PARALLEL FOR A LENGTH OF NOT LESS THAN 3⅜"
E
0·977" DIAR.
AREA ¾ SQ. IN.
3½" GAUGE LENGTH.
PARALLEL FOR A LENGTH OF NOT LESS THAN 4".

FIG. 155.

The very important case of tests for plates presented much greater difficulty. There is an enormous amount of this testing to be done, and the steel makers were very anxious that the standard tests should not be such as to cause any increase of cost or delay. They would have liked a uniform width of test bar prescribed for plates of all thicknesses, so that the test bars could all be milled to size in groups without shifting the milling heads. Also, they were anxious that, for simplicity, a fixed gauge-length should be prescribed. But then either the thick plates would have an advantage, or a different limit of elongation would have to be specified for each thickness of plate, and this is almost impracticable. After much discussion a compromise was arrived at. Three standard forms of plate test bar, A (fig. 155), of $2\frac{1}{2}$, 2, and $1\frac{1}{2}$ inches width, are arranged for plates under $\frac{3}{8}$ inch thick, plates $\frac{3}{8}$ inch to $\frac{7}{8}$ inch thick, and plates over $\frac{7}{8}$ inch thick. In an approximate way, the elongations in 8 inches in all these will be the same for the same material. The thicker plates are, in fact, a little favoured. The great bulk of all the testing will be done with the test bar 2 inches wide.

For plates $\frac{3}{8}$ and $\frac{7}{8}$ inch thick the gauge-length of the standard bar corresponds to $l = 9{\cdot}2\sqrt{\omega}$ and $l = 7{\cdot}2\sqrt{\omega}$, the thicker bar being a little favoured.

The following calculation shows how far the standard test bars ensure that the elongations of plates of different thicknesses are comparable. The elongation equation is—

$$\text{Elongation per cent} = e\% = \frac{c\sqrt{\text{A}}}{l} + b$$

where A is the cross-section of test bar, l the gauge-length, and c and b are constants for a given quality of material. From the large series of tests of mild steel boiler-plates the values of the constants may be taken to be for average steel—

Thickness of plates	c	b
$\frac{1}{4}$	94	18
$\frac{3}{8}$	81	20
$\frac{7}{8}$	70	19
$1\frac{1}{4}$	68	18·5

showing that, as might be expected from the less amount of rolling down, the thicker plates are less ductile. From these

values the following elongations for different standard test bars have been calculated :

Dimensions of test bar	Gauge-length	Area of section	Elongation per cent.
Inches	Inches	Sq. Inches	
$\frac{1}{4} \times 2\frac{1}{2}$	8	0·625	27·3
$\frac{3}{8} \times 2$	8	0·750	28·7
$\frac{7}{8} \times 2$	8	1·750	30·6
$1\frac{1}{4} \times 1\frac{1}{2}$	8	1·875	30·1

The thicker plates are slightly favoured by the proportions of test bar adopted.

169. *Influence of the Position of the Fracture on the Elongation.*—As the material of a test bar is not absolutely homogeneous and as the section is not absolutely uniform, the position of the fracture between the gauge-points cannot be predicted, and when the fracture occurs near the ends of the gauge-length the percentage of elongation is less than when it occurs near the centre. The following table gives some results obtained by the author, deduced from observations of test bars marked out in $\frac{1}{2}$-inch lengths. x is the distance of fracture from centre of gauge-length.

Elongation per cent. in 8 Inches, when the Fracture is not at the Centre of the Gauge-length

Number of bar . .	2361	2362	2363	2364	2365	2390	2391
Fracture at centre							
$x = 0$ . . .	29·2	29·5	29·8	25·3	29·0	26·7	30·5
$x = 1$ . . .	29·1	29·5	29·7	25·3	29·0	26·6	30·5
$x = 2$ . . .	28·9	29·5	29·8	25·3	29·0	26·6	29·7
$x = 3$ . . .	28·1	29·1	29·2	24·4	28·5	26·6	28·3
Fracture at gauge-point							
$x = 4$ . . .	23·5	23·9	24·4	20·2	24·1	23·2	23·5

In these tests the gauge-points were not near the enlarged ends. Where fracture occurs very near enlarged ends the elongation is further reduced by the influence of the enlarged ends. In the British Standard Specifications it is provided that if fracture occurs outside the middle half of the gauge-length, a new test may be made at the option of the manufacturer.

170. *Variation of Section between the Gauge-points.*—Small variations of cross-section have an appreciable influence

on the strength of bars, and a more serious effect on the elongation. Hence accurate preparation of test bars is more important than is generally recognised. Diegel has made tests of bars in which small variations of section were intentionally introduced. The bars were first very accurately turned, and then over a part 0·4 inch in length the section was reduced, the reduced part being connected with the rest of the bar by a conical part 0·6 inch long on each side. The following table gives the results:

EFFECT OF VARIATION OF CROSS-SECTION (DIEGEL)[1]

Material	Gauge-length	Diameter between gauge-points			Breaking stress. Tons per square inch reckoned on smallest section	Elongation per cent.
		Turned	Reduced near centre to	Reduction near centre		
	Inches	Inch	Inch	Inch	Tons	Per cent.
Martin steel	8	0·8	—	0·0	26·9	30·2
			0·796	0·004	27·1	25·3
			0·792	0·008	26·9	24·1
			0·788	0·012	27·2	21·5
			0·784	0.016	27·6	20·3
Martin steel	4	0·4	—	0·0	26·0	29·0
			0·396	0·004	26·3	23·9
			0·392	0·008	26·8	20·0
			0·388	0·012	26·1	18·2
			0·384	0·016	26·4	16·2
Crucible steel	8	0·8	—	0·0	30·8	29·0
			0·796	0·004	30·8	24·2
			0·792	0·008	31·1	22·2
			0·788	0·012	31·2	21·2
			0·784	0·016	31·3	19·1
Crucible steel	4	0·4	—	0·0	30·4	30·1
			0·396	0·004	31·0	21·9
			0·392	0·008	30·7	19·4
			0·388	0·012	31·2	17·4
			0·384	0·016	31·1	16·3
Special steel	4	0·4	—	0·0	53·1	14·8
			0·396	0·004	55·1	11·3
			0·332	0·008	53·3	10·6
			0·398	0·012	54·5	8·9
			0·384	0·016	54·9	8·7

[1] 'Der Einfluss von Ungleichmässigkeiten in Querschnitte des prismatischen Theiles eines Probestabes,' *Zeitschrift des Vereines Deutscher Ingenieure*, vol. xlvii. p. 426, 1903.

171. *Measurement and Marking-out of the Test Bar for a Tension Test.*—In careful testing the bar should be marked out in one-inch or half-inch lengths as in fig. 156, over the gauge-length or a little beyond it. Fig. 157 shows a marking-out gauge for scribing the distances, and a double punch

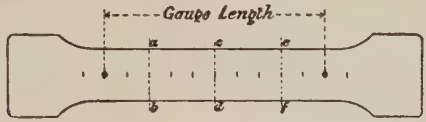


Fig. 156.

which serves the same purpose. It is, however, quite as convenient to use a beam compass, scribing off the lengths by putting one leg of the compass in the divisions of a metal divided scale. The test bar may be supported on V-blocks, and the scale fixed on a block at a convenient level.

As test bars are not of absolutely uniform section, and

Fig. 157.

the place of fracture cannot be foreseen, it is desirable to measure three cross-sections uniformly spaced along the gauge-length, and to take the mean as the section for calculation.

Thus, for a plate specimen, fig. 156, the measurement would be taken thus:

Widths		Thickness	
At *a b*	2·513	At *a*	0·251
„ *c d*	2·510	„ *c*	0·253
„ *e f*	2·515	„ *e*	0·254
		„ *b*	0·253
Mean.	2·513	„ *d*	0·252
		„ *f*	0·255
		Mean	0·253

Mean section $= 2{\cdot}513 \times 0{\cdot}253 = 0{\cdot}636$ sq. ins.

For round bars measurements may be made on three pairs of diameters at right angles. If necessary, punch marks are at this stage made on the sides of the bar, for attaching an extensometer or clips for the autographic apparatus.

172. *Limits of Accuracy in Tension Tests.*—Results in ordinary tests, the error of which is under one per cent., are no doubt accurate enough. In any case they should not be reported with a precision in excess of the accuracy of the observations. The French Commission ruled that in ordinary testing intended to be valuable for comparison, the error should not exceed 50 lbs. in loads less than 5 tons, or 100 lbs. in loads above 5 tons. Also that linear measurements should be accurate to $\frac{1}{600}$ inch for lengths under half an inch, and to $\frac{1}{2\,1\,5\,0}$ inch in greater lengths. In deciding on the limit of proportionality or real elastic limit they were of opinion that the deviation from proportionality should not exceed $\frac{1}{2\,5\,0\,0\,0}$ of an inch, in a gauge-length of 8 ins., for an increment of load of about 0·7 ton per sq. in.

Observations during a Tension Test. — Ordinarily the data observed are (*a*) the load at the yield point; (*b*) the so-called breaking load, which in practice is the maximum load before breaking; (*c*) the elongation after fracture; (*d*) the contraction of area.

(*a*) can be determined in rough tests either by noting with a pair of dividers the moment at which a visible stretch between two punch marks is observable, or by noting the moment when a sudden drop of the lever indicates a sudden stretch of the bar. It is best determined by taking an autograph diagram. After the broken parts of the bar are removed from the testing-machine they are carefully placed together, supported on wood blocks and wedges, and the elongation and contraction of area are measured. The contraction of area, from the irregular form of the fracture, cannot be measured with great accuracy.

Example of Calculation of Tension Test.
Mild steel bar No. 1435, mark s.
Dimensions, 1·960 × 0·405 = 0·7936 sq. in. area.
Load at yield point (from diagram), 14·6 tons.
Maximum load, 25·09 tons.
Actual breaking load, 21·84 tons.
Extension in 8 inches, 2·44 inches.
Contracted dimensions, 1·408 × 0·272 = 0·3830 sq. in.

From these observations the following results are calculated :

Stress at elastic limit = 14·6 / 0·7936 = 18·39 tons per sq. in.

Breaking stress = 25·09/0·7936 = 25·09 tons per sq. in.

Ratio of elastic to breaking stress = 18·39/25·09 = 0·73.

Elongation per cent. = 2·44/8 × 100 = 30·5 per cent.

Contraction $\frac{0{\cdot}7936-0{\cdot}3830}{0{\cdot}7936} \times 100 = 51{\cdot}7$ per cent.

The calculations are conveniently made by a Fuller's Slide Rule. On the next page is a convenient form for recording the final results. The work done in breaking the bars has been measured from an autographic diagram.

173. *Measure of Ductility.*—In specifications either the percentage of elongation in the gauge-length or the percentage of contraction of area is taken as the measure of ductility. The latter is known to be much affected by small local defects at the section of fracture. Both are merely empirical measures of ductility. It has been proposed to take the percentage of extension at maximum load as the measure of ductility, and this would be almost completely independent of the form of the test bar. But it is difficult to ascertain unless an autograph diagram is taken.

It is easy, however, to measure the elongation after fracture on two gauge-lengths, say 4 ins. and 8 ins. Let λ_1, λ_2, be the elongation in gauge-lengths, l_1, l_2, of any broken bar. Then, if x is the general elongation per unit length, and a the local extension independent of the length—

$$\lambda_1 = xl_1 + a,$$
$$\lambda_2 = xl_2 + a.$$

General extension per unit length $= x = (\lambda_1-\lambda_2) / (l_1-l_2)$ and local extension $= a = \lambda_1-xl_1$.

Report on Specimens of .....

.....

Received from .....

Date .... 18..... *on the* ..... 18.....

Test No.	Marks on specimen	Dimensions in inches		Section in sq. in.	Stress at elastic limit in tons per sq. in.	Maximum stress in tons per sq. in.	Ratio of elastic to maximum stress	Elongation in 8 ins. per cent.	Elongation in..... in. per cent.	Contraction of section per cent.	Work done up to max. stress in in.-tons per c. in.	Remarks
		Width	Thick									
142	L	3·502	0·400	1·401	16·4	23·2	0·71	20·7	—	22·4	3·55	Lowmoor iron
140	X	3·500	0·258	0·903	18·3	23·0	0·80	10·8	—	15·9	2·29	„ „
360	S	3·238	0·369	1·195	16·8	21·5	0·77	7·1	—	8·0	—	Best Staffordshire iron

Besides the contraction of area at fracture there is another measure which might be taken, viz. the rate of extension at the fracture. If ω is the initial section of the bar and $\omega - c$ the section after fracture, so that c is the contraction of area, then the rate of ultimate extension at the point of fracture is $c/(\omega - c)$. The following table contains a comparison of these different quantities for a series of rails. They are arranged in the order of the percentage of carbon, but of course the carbon, though the most important, is not the only hardening constituent.

STEEL RAILS

No.	Per cent. of carbon	Measured elongations in inches		Elongations per cent.			Local extension, a, in ins.	Contraction of area per cent. $100c$	Extension at fracture per cent. $100\frac{c}{\omega - c}$
		In 8 ins. λ_1	In 4 ins. λ_2	In 8 ins.	In 4 ins.	General $100x$			
1	·291	1·200	0·740	15·0	18·5	11·5	·280	35·2	54·3
2	·329	1·520	1·008	19·0	25·2	12·8	·496	43·8	78·0
3	·335	1·344	0·912	16·8	22·8	10·8	·480	41·0	69·5
4	·338	1·496	0·952	18·7	23·8	13·6	·408	40·5	68·0
5	·371	1·392	0·932	17·4	23·3	11·5	·472	37·7	60·5
6	·371	1·128	0·772	14·1	19·3	8·9	·416	37·8	60·7
7	·374	1·544	1·008	19·3	25·2	13·4	·472	39·7	65·7
8	·386	1·208	0·836	15·1	20·9	9·3	·464	38·8	63·5
9	·398	1·368	0·804	17·1	20·1	14·1	·240	22·7	29·4
10	·412	1·288	0·856	16·1	21·4	10·8	·424	38·9	63·8
11	·415	1·008	0·696	12·6	17·4	7·8	·384	33·6	50·5
12	·454	1·344	0·832	16·8	20·8	12·8	·320	33·4	50·1

All the measures a, $100c$, and $100c/(\omega - c)$ are affected by small local defects in the plane of fracture. It seems probable that the low values for 1 and 9 are due to this cause. Arranged in order of percentage of carbon, and omitting 1 and 9, the values of a, $100c$, and $100c/(\omega - c)$ are all in fairly regular order. The values of $100x$ are in less regular order. On the whole, the values of $100c/(\omega - c)$ seem to agree best with the carbon per cent. so far as that indicates the character of the material. The following table gives the same results, but arranged in the order of the tenacity of the steel:

STEEL RAILS

No. in previous table	Tenacity in tons per sq. in.	Elongations per cent.			Local extension a	Contraction of area, per cent. $100\,c$	Extension at fracture per cent. $\frac{100\,c}{\omega - c}$
		In 8 ins.	In 4 ins.	$100\,x$			
2	36·4	19·0	25·2	12·8	·496	43·8	78·0
4	36·9	18·7	23·8	13·6	·408	40·5	68·0
9	37·1	17·1	20·1	14·1	·240	22·7	29·4
7	37·6	19·3	25·2	13·4	·472	39·7	65·7
1	38·9	15·0	18·5	11·5	·280	35·2	54·3
3	39·4	16·8	22·8	10·8	·480	41·0	69·5
5	39·5	17·4	23·3	11·5	·472	37·7	60·5
8	40·1	15·1	20·9	9·3	·464	38·8	63·5
12	41·4	16·8	20·8	12·8	·320	33·4	50·1
10	43·7	16·1	21·4	10·8	·424	38·9	63·8
6	45·3	14·1	19·3	8·9	·416	37·8	60·7
11	50·5	12·6	17·4	7·8	·384	33·6	50·5

Arranged in order of tenacity it will be seen that the values of the general extension $100x$ fall more nearly into regular order.

174. *Tetmajer's Coefficient of Quality.*—The work done in breaking a bar, depending as it does both on the strength and ductility, is a criterion of the value of a material for structural purposes. But, except by taking the area of an autographic diagram of a test, the work cannot be exactly ascertained.

Let f be the maximum load reckoned in tons per sq. in.,
e the ultimate elongation per inch length, that is the percentage of elongation divided by 100.

Then the work done in breaking the bar in inch-tons per cubic inch of bar is—

$$u = c f e,$$

where c is a coefficient expressing the ratio of the area of the stress-strain diagram to that of a rectangle enclosing it. Tetmajer found that for material of similar kind, and for test bars of similar form, c was nearly a constant, so that the work done might be taken to be proportional to fe. Hence,

the product fe is a measure of quality which may be termed Tetmajer's coefficient.

For ordinary good steel the value of Tetmajer's coefficient is about 6·7. Hence, the percentage of elongation to be expected in a steel of f tons breaking-stress per sq. in. is $100 \times 6{\cdot}7 / f = 670/f$. It should, however, be remembered that it is only in similar test bars, or with a constant gauge-length test bars of not widely different size, that the coefficient will be an approximate measure of relative quality.

175. *Elastic Limit and Yield Point in Commercial Tests.*— In some specifications an elastic limit or yield point is stated, but there is much confusion both in the use of the terms and in the methods of determining them. It is really the yield point which is required, though the elastic limit is often specified.

The elastic limit in a tension test is the stress per unit of cross-section at which the extensions begin to increase faster than the stresses or at which proportionality of strains and stresses ceases. It can be determined by increasing the load by equal small increments and observing the extensions by a delicate extensometer. The elastic limit is the stress at which the first differences of the extensions distinctly cease to be constant. The elastic limit is not so fixed a point as is commonly supposed. In the first loading of a bar small sets are sometimes observed due to the settlement of the test bar in the grips, to straightening or small defects of homogeneity. It is usual to load a bar once or twice to a stress approaching the elastic limit before taking observations to determine it. The limit so found is the *primitive* elastic limit. But the elastic limit does not depend on the material only. The primitive elastic limit is generally an artificially raised limit. By cyclical variations of stress its position can be changed, a point discussed in Chapter V. Further, the determination of the elastic limit involves observations much more delicate than are suitable or possible in commercial testing.

The true characteristic of a yield point is the large increase of extension without increase of load. It is a point strongly marked in mild and medium steel and wrought iron, but it is absent in hard steel and most alloys. For the purpose of commercial testing the yield point may be defined to be the load per sq. in. of cross-section at which a distinctly

visible increase occurs in the distance between gauge-points on the test bar, observed by using dividers, or at which when the load is increased at a moderately fast rate there is a distinct drop of the testing-machine lever, or in hydraulic machines of the gauge-finger. A 'distinctly visible increase' may be taken to be about one-two-hundredth of the gauge-length. In cases where a yield point can be usefully observed, the extension is so large that this statement is quite definite enough. The attempt sometimes made to define arbitrarily a yield point for materials which have no distinct yield point, and often as manufactured no elastic limit either, appears to the author to be useless and misleading.

Example of the Determination of the Coefficient of Elasticity by a Tension Test

BAR OF MILD STEEL, No. 1049

Width $= b = 1{\cdot}816$ in.; thickness $= t = 0{\cdot}6316$ in.; area $= \omega = 1{\cdot}147$ sq. in. Extensions measured on 7-in. length by screw extensometer

Load on bar in tons	Stress in tons per sq. in.	Micrometer reading, inches	Differences. Extensions per 2 tons per sq. in.	Total extension in inches
0	0	—		0
1·147	1	·00170		[·00052]
3·441	3	·00275	·00105	·00157
5·735	5	·00380	·00105	·00262
8·029	7	·00485	·00105	·00367
10·323	9	·00590	·00105	·00472
12·617	11	·00695	·00105	·00577
				Set
1·147	1	·00170		0

Here, for a range of stress from 1 to 11 tons per sq. in., the elastic extension is 0·00105 inch in 7 inches per 2 tons per sq. in.

$$\text{Coefficient of elasticity} = \text{E} = \frac{2 \times 7}{\cdot 00105} = 13{,}333 \text{ tons per sq. in.}$$

The bar had previously been strained nearly to its elastic limit. The elongation for one ton per sq. in. was not measured, but calculated from the extension between 1 and 3 tons per sq. in.

176. *Example of a Transverse Test.*

RECTANGULAR BAR OF TIMBER LOADED AT CENTRE AND SUPPORTED AT THE ENDS

Section; width = b = 2·95 ins.; depth = d = 2·97 ins.; span = l = 40 ins.

Load, lbs.	Micrometer reading, inches	Increment of deflection for each increment of load	Total deflection at centre, in inches	Mean elastic deflection for 500 lbs. load, inches
0	·195	—	—	
500	·252	·057	·057	
1,000	·312	·060	·117	
1,500	·372	·060	·177	δ = 0·0585
2,000	·430	·058	·235	
2,500	·488	·058	·293	
3,000	·546	·058	·351	
3,500	·620	·074	·425	for
4,000	·701	·081	·506	Δ w = 500
4,500	·850	·149	·655	
5,000	1·380	·530	1·185	

Broke by tension with load of 5,000 lbs. after 2 minutes.

Here 3,000 lbs. may be taken as the load at the limit of elasticity, being the greatest load for which the increments of deflection are nearly constant, and 5,000 lbs. is the breaking load.

Coefficient of breaking strength

$$= f = \frac{3 \times \mathrm{w} \times l}{2 \times b \times d^2} = \frac{3 \times 5{,}000 \times 40}{2 \times 2{\cdot}95 \times 2{\cdot}97^2} = 11{,}530 \text{ lbs. per sq. in.}$$

$$= 5{,}147 \text{ tons per sq. in.}$$

Stress at elastic limit

$$= f = \frac{3 \times \mathrm{w} \times l}{2 \times b \times d^2} = \frac{3 \times 3{,}000 \times 40}{2 \times 2{\cdot}95 \times 2{\cdot}97^2} = 6{,}918 \text{ lbs. per sq. in.}$$

$$= 3{\cdot}09 \text{ tons per sq. in.}$$

Coefficient of elasticity

$$= \mathrm{E} = \frac{\Delta \mathrm{w} \times l^3 \times 12}{48 \times \delta \times b \times d^3} = \frac{500 \times 40^3 \times 12}{48 \times 0{\cdot}0585 \times 2{\cdot}95 \times 2{\cdot}97}$$

$$= 2{,}280{,}000 \text{ lbs. per sq. in.}$$

$$= 1{,}018 \text{ tons per sq. in.}$$

177. *Bending and Temper Tests.*—An extremely useful test of the ductile quality of the material is the cold bending test in common use in workshops. A strip 1 to 3 inches wide and 6 to 10 inches long is bent by a lever, by hammering or by steady pressure, till either the two ends are parallel or

cracks appear. The strip may be tested in three conditions: (*a*) normal, as received; (*b*) annealed; (*c*) quenched —that is, heated to cherry red (1,000° to 1,200°) and plunged into water at about 80° F. The steel must be very bad if it cracks after annealing. Good mild steel should bend to as great an angle after quenching as in its normal state. The strips for bending should be planed at the sides.[1] If merely sheared, the test is more severe and less trustworthy. With thick plates (over 1 inch thick) few will stand any bending if the edges are sheared. Sometimes the strips are bent close. More generally they are bent over a rounded edge of a prescribed diameter.

A good deal of experimental work was carried out for the Standards Committee, chiefly by Mr. Bernard Firth, with the object of regularising the bend tests of ductile material. The result was a recommendation that such tests should be carried out by the pressure of a plunger and not by hammering. The test piece for plates is not less than $1\frac{1}{2}$ inch wide, and bent to a radius equal to 1·5 times the thickness, through 180°, without cracking. For marine forgings the test piece is 1 inch wide, $\frac{3}{4}$ inch thick, and 5 inches long. This is bent by a hydraulic plunger through an angle of 180°, or till the two segments are parallel. The radius of the end of the plunger, or radius inside the bend of the test bar, is made to vary with the tensile strength of the steel in the following way:

Range of tensile strength. Tons per square inch.	Radius inside bend. Inch.
28–32	$\frac{1}{4}$
32–36	$\frac{3}{8}$
36–40	$\frac{1}{2}$

For marine steel castings the bend test bar is 1 inch wide by $\frac{3}{4}$ inch thick, and is to bend without cracking through angles of 60° to 120°, according to the grade required.

For locomotive axles and forgings the bend test bar is 9 inches × $1\frac{1}{4}$ inches × $1\frac{1}{4}$ inches. The corners rounded to a radius of $\frac{1}{16}$ inch. It is bent over a bar $2\frac{1}{2}$ inches diameter to an angle of 90°. The ends are brought together after removing the bar over which it has been bent, and it should show no cracks. For steel castings for rolling stock the bend test bar is 9 inches long and 1 inch diameter. It should bend to 90° without cracking.

[1] In the temper test the shearing of the strip does not seem injurious.

178. *Methods of bending Test Bars.*—The roughest method of carrying out a bend test is to fix the strip in a vice and clamp a lever to it long enough to bend it. The bending may be completed by blows of a hammer.

One way of applying the bending test is to place the strip on supports 6 to 10 inches apart, and bend it by pressure in the testing-machine to an angle of about 90°, as in fig. 158, *a*. The bending may then be continued as in

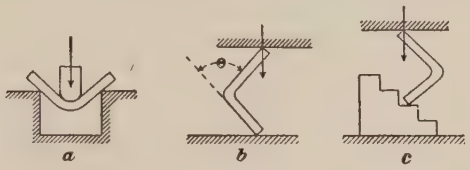


Fig. 158.

fig. 158, *b*. A stepped block, as in 158, *c*, facilitates this latter operation. If the strip cracks the bending is stopped, and the angle θ through which the strip has been bent is noted.

A lever apparatus for quietly bending strips of plate is

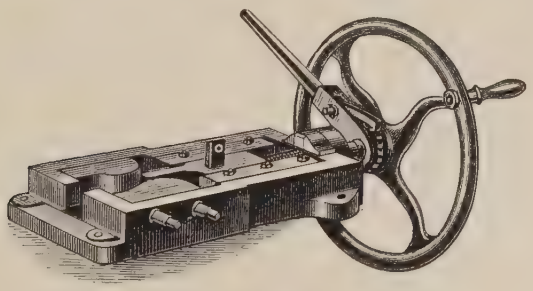


Fig. 159.

sometimes used. Fig. 159 shows a small apparatus introduced by Mr. A. H. Kuhlmann. It has a screw worked by a hand-wheel or by a ratchet lever. It will bend strips 2 inches wide and $\frac{3}{4}$ inch thick. Large bending machines driven by power on the same principle are made for use in steel works.

Hot Bending Test.—Sometimes the bending test is applied to a strip at red heat, in order to detect '*red shortness*.'

Drifting Test. — Another workshop test of ductility is to drill a hole near the edge of a piece of plate 4 or 6 inches square, and then to enlarge it by a conical drift till it is at least twice its original size, or till cracks appear. Commonly the hole is $\frac{5}{8}$-inch diameter, and at $1\frac{1}{4}$-inch from the edge of the plate. The hole in good mild steel may be enlarged to $1\frac{1}{2}$-inch diameter without cracks appearing.

Forging Test.—Rivet bars are sometimes heated to full red heat and then forged flat by a heavy hammer till cracks appear at the edges. Welding tests are made in this way. Pieces of about one square inch in section are prepared for a scarf weld. The pieces are then heated in a coke or gas furnace having a true reducing flame. At white heat they are removed, welded, upset, and drawn down to normal size by a hammer of 8 or 10 lbs. weight without reheating. The bar should then be tested by tension in its rough state, or nicked to the plane of the weld and bent to show the character of the welded surfaces.

179.—*Tests by Shock or Impact or Drop Tests.*—In the opinion of many engineers there are qualities of iron and steel which are only to be determined by breaking them by a sudden blow. Sometimes for cast iron, generally for rails, tyres, and axles, tests by impact with a falling weight are specified. Sometimes the test required is that the tyre or axle should stand a certain number of blows of a given weight falling from a certain height without failure. In the case of axles, the piece tested is turned through 180° after each blow. In other cases, as in the case of rails, the weight is allowed to drop from gradually increasing heights till, if possible, it is broken, and its quality is judged by the amount of hammering it stands before breaking.[1]

A specification for locomotive axles sometimes requires that they shall sustain without failure a ton falling 30 feet five times or a ton falling 25 feet sixteen times, the axle being on supports $3\frac{1}{2}$ feet apart. Ordinary railway carriage and waggon axles may be required to sustain one ton falling 20 feet five times, the span being $3\frac{1}{2}$ feet.

[1] An examination of the relative effect of different weights of monkey, and different heights of fall, &c., will be found in a paper by Professor A. Martens, 'Ueber Material prüfung durch Slagversuche,' *Mitt. aus dem Versuchsanstalten zu Berlin*, 1891. A discussion of the arrangement of impact-testing machines will be found in the *Report of French Commission on Testing*, vol. iii. p. 229.

EXAMPLE OF AN IMPACT TEST

Steel rail, weight per yard 82 lbs. Placed on supports 3 ft. apart, head down. Weight of monkey, 1 ton.

No. of blow	Height of fall in feet	Permanent deflection in inches	Work done in foot-tons
1	1	·125	1
2	2	·375	2
3	3	·625	3
4	4	1·000	4
5	5	1·5	5
6	6	2·0	6
7	7	2·68	7
8	10	3·625	10
9	20	Broke	20
Total			58

180. *Tests for Cast Iron.*—Transverse tests are made on bars cast in dry sand moulds with a head of 6 ins., pouring being done at two gates. Sometimes vertical casting is required. The bars are usually 1 in. × 1 in. × 40 ins., and broken with a centre load on supports 36 ins. apart. The breaking strength and ultimate deflection are noted, sometimes also the coefficient of elasticity. The Munich Conference recommended bars 1·2 in. square, 44 ins. long, the span to be 40 ins. Tension tests of cast iron may be made on turned bars $\frac{7}{8}$-in. diameter with 8-in. gauge-length. Bars with screwed ends held in the shackles by nuts with a spherical seating are most satisfactory. Compression tests are sometimes made on cylinders or square prisms of a height one and a half times the diameter or length of side.

EXAMPLE OF A TRANSVERSE TEST OF A CAST-IRON BAR

Breadth $= b = 1{\cdot}02$ in.; depth $= d = 1{\cdot}04$ in.; span $= l = 25$ ins.

Load, lbs.	Micrometer reading	Increment of deflection for load increment of 200 lbs., in ins.	Total deflection, inches	—
0	2·00			
200	2·05	·05	·05	For load increment $\Delta W =$ 200 lbs. the mean elastic deflection is $\delta = 0{\cdot}045$ in.
400	2·09	·04	·09	
600	2·13	·04	·13	
800	2·18	·05	·18	
1,000	2·22	·04	·22	
1,200	2·29	·07	·29	
1,400	2·36	·07	·36	
1,500	2·40	·04	·40	
1,600	2·45	·05	·45	
Broke				

Here the elastic limit may be taken at 1,000 lbs., up to which the deflections for 200 lbs. are approximately constant.

$$\text{Coefficient of elasticity} = \text{E} = \frac{\Delta\, w\, l^3}{48\, \delta_J}$$

$$= \frac{\Delta\, w\, l^3}{4\, b\, d^3\, \delta} = 15{,}230{,}000 \text{ lbs. per sq. in.}$$

Coefficient of breaking strength

$$= f = \frac{3\, w\, l}{2\, b\, d^2} = 54{,}540 \text{ lbs. per sq. in.} = 24{\cdot}36 \text{ tons per sq. in.}$$

181. *Shearing and Torsion Test Specimens.*—Fig. 160 shows a specimen prepared for shearing of the form used by

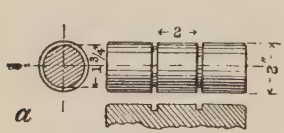


Fig. 160.

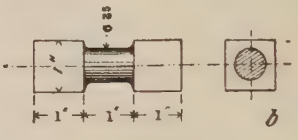


Fig. 161.

Professor Kennedy. Two narrow grooves are cut, so that the shearing planes are defined. Fig. 161 shows Thurston's form of torsion test piece, the ends being square to fit the shackles and the centre part cylindrical. A better form for torsion test bars is given in fig. 104.

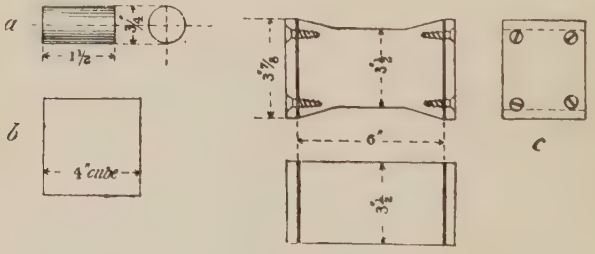


Fig. 162.

182. *Test Specimens for Crushing.*—Fig. 162 shows the ordinary forms of test specimens for compression. For metals such as iron, steel, cast iron, or brass, small cylinders *a* are used. For cement, stone, &c., cubes, as at *b*. For wood, Bauschinger has found it to be desirable to protect the ends with a metal plate, a sheet of paper being interposed. The form he adopts is that shown at *c*.

CHAPTER XII

ELASTIC CONSTANTS FOR METALS

183. *Coefficient of Direct Elasticity.*—The accurate determination of the coefficients of elasticity and limits of elasticity depends on the measurement of extremely small deformations. Some of the practical difficulties of measurement have been discussed in Chapter IX. For many materials the elastic constants change with the amount of stress applied and with every repetition of stress, and there is not complete agreement as to the definition of the constants or the methods of determining them.

Let it be proposed to determine the coefficient of elasticity from observations on a cast-iron bar. By definition the coefficient of direct elasticity is $E = p/\lambda$ where p is the stress per unit area and λ the corresponding extension per unit length. It would be found (1) that p/λ varied for different ranges of stress, and (2) that it differed in successive loadings of the bar. The total extension consists of a part λ_e which vanishes on removal of the stress and a set λ_s which remains. If the coefficient of elasticity is taken to be $E' = p/\lambda_e$ values are obtained which vary less with range or repetition of stress. The following table contains Hodgkinson's results for the tension and compression of long bars of cast iron. These results on long bars are chosen because, although the methods of measurement were somewhat crude and rough, they are free from any possible objection arising out of complexity in the measuring apparatus. It will be seen that both E and E' diminish as the stress increases, but that E' varies much less than E. The coefficients are in tons per sq. in. The next table contains some results on bars of gun-barrel steel, made by the Committee on Steel, and which are chosen for similar reasons. For wrought iron and steel the set in the earlier part of the test is comparatively insignificant. Yet E' is more constant than E, even in the earlier part of the

HODGKINSON'S EXPERIMENTS ON CAST-IRON BARS. MEAN RESULTS ON NINE BARS, REDUCED TO 10-FEET LENGTH AND 1 SQ. IN. AREA.

TENSION						PRESSURE					
Stress in tons per sq. in. p	Total extension in inches $120\,\lambda$	Total set in inches $120\,\lambda_s$	Total elastic extension $120\,\lambda_e$	Ordinary coefficient of direct elasticity E	Coefficient E′	Stress in tons per sq. in. p	Total compression in inches $120\,\lambda$	Total set in inches $120\,\lambda_s$	Total elastic compression $120\,\lambda_e$	Ordinary coefficient of direct elasticity E	Coefficient E′
·9404	·0186	·0006	·0180	6,067	6,269	·9212	·0188	·0005	·0183	5,879	6,039
1·881	·0391	·0018	·0373	5,775	6,053	1·843	·0388	·0023	·0365	5,701	6,059
2·821	·0613	·0037	·0576	5,525	5,879	2·765	·0598	·0040	·0558	5,549	5,947
3·762	·0859	·0066	·0793	5,257	5,694	3·685	·0788	·0065	·0723	5,611	6,116
3·703	·1136	·0106	·1030	4,968	5,480	4·607	·0994	·0085	·0909	5,560	6,080
5·644	·1448	·0161	·1287	4,677	5,262	5·530	·1203	·0109	·1094	5,516	6,066
6·603	·1859	·0241	·1618	4,262	4,898	6·451	·1416	·0141	·1275	5,467	6,071

test, and is nearly constant even for stresses considerably beyond the elastic limit. For wrought iron and steel E diminishes as the breaking weight is approached.

EXPERIMENTS OF STEEL COMMITTEE

(Bars, 1¼ in. in diameter. Extensions and compressions in 10 feet)

Stress in tons per sq. in. p	Total extension in feet $120\,\lambda$	Set in feet $120\,\lambda_s$	Elastic extension in feet $120\,\lambda_e$	Ordinary coefficient of direct elasticity E	Coefficient E′
			TENSION		
6·80	·0053	—	—	12·830	12·830
7·94	·0062	—	—	12·800	12·800
9·07	·0071	·0001	·0070	12·770	12·960
10·21	·0079	·0002	·0077	12·920	12·260
11·34	·0089	·0002	·0087	12·750	13·030
12·48	·0098	·0003	·0095	12·740	13·140
13·61	·0104	·0004	·0104	12·600	13·090
17·01	·0143	·0016	·0127	11·900	13·400
			PRESSURE		
6·92	·0047	—	·0047	—	—
10·38	·0078	·0001	·0077	13·300	13·480
13·84	·0105	·0003	·0102	13·180	13·570
15·28	·0117	·0006	·0111	13·060	13·770
16·15	·0125	·0007	·0118	12·920	13·690
17·31	·0138	·0011	·0127	12·540	13·620
18·46	·0172	·0035	·0137	10·740	13·480

No doubt in most cases values of E are given as the coefficient of elasticity, and it will be understood that it is so in what follows. But then materials like cast iron and all the brasses and bronzes have no definite coefficient of elasticity.

184. If in loading a bar the yield point is passed, the material is altered, and this is shown in an alteration of the coefficient. With a rest of a day or more after loading, the bar recovers, so that the alteration of the coefficient is less. The following table gives some results from Bauschinger's paper on the 'Change of the Elastic Limit':[1]

[1] *Civilingenieur*, 1881.

COEFFICIENT OF DIRECT ELASTICITY IN SUCCESSIVE LOADINGS OF THE SAME BAR IN TONS PER SQ. IN. (BAUSCHINGER)

Material	First loading	Second loading	Third loading	Fourth loading
Bars unloaded and reloaded immediately				
Weld iron	13,080	12,470	12,360	12,300
„ „	13,080	12,640	—	11,930
Ingot iron	13,960	—	14,060	13,610
„ „	14,460	14,170	13,370	12,600[2]
Copper	7,436[1]	7,702	7,214	7,042
Bronze	5,372	5,575	5,683	—
Bars unloaded and reloaded after a pause varying from 3 to 80 hours				
Weld iron	12,970	12,920	12,590	12,610
„ „	13,040	12,680	12,720	12,580
„ „	13,080	12,860	12,600	12,810
„ „	13,270	12,790	12,720	12,900[2]
„ „	12,800	12,780	12,760	13,210[2]
Ingot iron	14,240	14,270	14,240	17,470
„ „	14,530	14,400	14,390	13,880[2]
„ „	14,500	14,180	14,150	14,100[2]
Bessemer steel	13,330	13,200	12,950	13,460
Copper	7,150[1]	7,278	7,144	7,036
„	7,188[1]	7,494	7,176	6,910
Bronze	5,503	5,499	5,575	—

The differences of the coefficients for the same bar may seem not very large, but they are large compared with the variation of the coefficient in different qualities of the same material, and, indeed, in some cases exceed 10 per cent.

185. *Values of* E *for Different Materials.*—The following are values of the modulus of elasticity for iron and steel. Kupffer's values were obtained by bending and transverse vibrations, and represent values of the coefficient for small stresses:

COEFFICIENT OF DIRECT ELASTICITY (KUPFFER)

—	Density	Coefficient E in tons per sq. in.
Iron plate, in direction of rolling	7·676	11,200
„ „ across „ „	7·678	12,160
Rolled English band iron	7·643	12,710
„ „ bar iron	7·641	12,850
Forged Swedish „	7·832	13,560
Soft cast steel	7·842	13,540
Steel adapted for files	7·819	13,440

[1] Yield point not reached in first loading.
[2] Vibrated after each loading.

The following table gives values of the coefficient, determined by Knut Styffe, for iron and steel.[1] In these experiments the coefficient increases slightly by annealing. Styffe also made experiments on the change of the coefficient with change of temperature. He found that it decreased about 0·03 per cent. for each degree rise of temperature (Centigrade). After a permanent stretching of the bar it diminished by 4 to 9 per cent.

COEFFICIENT OF DIRECT ELASTICITY OF IRON AND STEEL FROM TENSION EXPERIMENTS (STYFFE)

—	Probable percentage of carbon	Coefficient E in tons per sq. in.	
		Initially	After heating to slight redness
Hammered Bessemer steel . .	1·35	—	14,220
„ „ „ . .	1·26	13,450	13,640
„ „ „ . .	1·05	13,660	14,060
„ „ iron . .	0·1	14,430	—
„ „ „ . .	0·15	15,290	15,440
Rolled cast steel	1·22	13,940	—
Krupp „	0·61	14,000	14,340
Rolled puddled steel . . .	0·66	—	13,540
„ „ „ . . .	0·56	13,360	—
Lowmoor iron	0·2	14,280	—
Dudley „	0·09	12,680	—
„ „	0·09	12,260	—
Motala „	0·05	13,510	13,740
„ „	0·2	13,200	—
Surahammar iron . . .	0·14	13,880	—
„ „ . . .	0·2	13,610	13,720
Charcoal iron (Aryd) . . .	0·1	11,960	—
„ „ „ . . .	0·1	12,410	13,050
„ „ (Hallstahammar) .	0·07	12,940	—
„ „ „ .	0·07	13,760	13,760

The following are values for steel, obtained by Bauschinger,[2] and are interesting as giving the coefficient for bending, tension, and pressure. The coefficient of rigidity was also determined by experiment on torsion. From the values of E and G values of Poisson's ratio $1/m$ have been deduced.

[1] *Iron and Steel.* Styffe. Translated by Sandberg, p. 147.
[2] Reduced from tables in *Civilingenieur*, 1879.

COEFFICIENT OF ELASTICITY. BESSEMER STEEL FROM TERNITZ

Percentage of carbon	Coefficient of direct elasticity, E				Coefficient of rigidity, C	$\frac{1}{m}=\frac{E}{2C}-1$
	From tension tests	From pressure tests	From bending tests	Mean	From torsion tests	
0·19	13,780	16,540	13,020	14,730	5,575	·32
0·46	14,300	14,640	13,090	14,220	5,420	·30
0·54	13,690	16,140	12,900	14,480	5,450	·33
0·57	13,720	14,290	13,080	13,840	5,320	·30
0·66	14,480	15,940	14,350	15,040	5,520	·36
0·78	14,980	14,480	13,460	14,480	5,405	·34
0·80	13,660	14,440	14,730	14,160	5,670	·25
0·87	13,880	14,100	13,590	13,900	5,400	·29
0·96	13,820	14,640	13,080	13,970	5,560	·26
					Mean	0·305

SIEMENS-MARTIN STEEL FROM NEUBERG-MARIAZELL

Degree of hardness	Coefficient of direct elasticity, E			Coefficient of rigidity, C	$\frac{1}{m}=\frac{E}{2C}-1$
	From tension tests	From bending tests	Mean		
7	13,450	13,520	13,460	5,470	·25
6	13,090	13,340	13,210	5,260	·25
5	13,370	13,480	13,400	5,295	·27
4	13,390	13,430	13,400	5,401	·21
3	13,620	13,390	13,340	5,150	·30
				Mean	0·262

The following values are from experiments at Watertown Arsenal and are, it is believed, values obtained after deducting the permanent set. They are values of E′ therefore.

Wrought iron	Coefficient of elasticity, E		
	Highest	Lowest	Mean
For 10 rolled bars, single refined	13,790	12,040	12,540
For 9 „ „	13,100	12,310	12,530
For 10 „ double refined	15,200	12,335	12,950
For 9 „ „	13,105	11,410	12,680
For 10 Phœnix eye-bars . .	12,070	9,996	11,150
For 6 steel „ . .	13,510	13,230	13,345

Thurston has obtained from bending experiments the following values for the bronzes. The values given are

for small stresses, the coefficient diminishing with increase of stress just as in cast iron. Some other values are added:

COEFFICIENT OF ELASTICITY

E in tons per sq. in.

Gold	5,479	Meyer
„ (drawn)	5,162–5,486	Wertheim
Silver (drawn)	4,826	„
Platinum	10,170	Meyer
„ (wire)	10,710	Wertheim
Nickel	13,780	Meyer
Cast copper	6,240–4,555	Thurston
Copper (hard drawn)	5,580	Wertheim
„ (annealed)	5,133	„
Cast zinc	3,118	Thurston
Zinc (drawn)	5,525	Wertheim
Cast tin	3,006	Thurston
Lead	1,116	Wertheim
Cast iron	4,250–7,700	Stromeyer
Brasses	5,130–6,580	Thurston
Bronzes	5,935–6,840	„
Brass (rolled)	5,800	Bauschinger
Muntz metal	5,800–6,700	Stromeyer
Manganese bronze	6,100	„
Aluminium bronze	6,704–6,536	Unwin
Delta metal	5,555–6,060	„
Gun metal	4,762–5,376	„
Phosphor bronze	5,950	„
Steel castings	8,400–14,000	„

186. *The Elastic Limit.*—The term elastic limit belongs to the theory of the strength of materials, and it has a rational meaning. It is the limit up to which stresses and strains are proportional, and for that reason is sometimes called the limit of proportionality. Its determination requires the observation of increments of strain for small increments of load, and therefore involves very accurate measurements.

The following measurements of extension of a piece of iron from old Hammersmith Bridge show how the limit of proportionality can be determined. In this case the limit in successive loadings, none of which reached much beyond the elastic limit, slowly rises.

Link from old Hammersmith Bridge, received from Sir B. Baker. This was planed all over to get surfaces for accurate measurement, and its section was about $1\frac{3}{4}$ sq. in. Extensions for each ton per sq. in., taken with mirror apparatus:

Load in tons per sq. in.	Distance of gauge-points, 7·94 ins. Extensions per ton in $\frac{1}{100000}$th of an inch			
	First loading	Second loading	Third loading	Fourth loading
1	—	—	—	—
2	55	58	54	58
3	57	56	56	56
4	58	58	58	58
5	58	57	58	58
6	58	58	58	58
7	58 E. L.	57	58	58
8	61	59 E. L.	58 E. L.	58
9	60	60	60	58 E. L.
10	62	60	59	60
11	—	—	—	63
12	—	—	—	75
Set, load removed	+ 13	− 2	+ 2	+ 32

Elastic range	Total extension	Mean extension per ton per sq. in.
1st loading, 1 to 7 tons . .	0·003437	0·000573
2nd „ 1 to 7 „ . .	0·003449	0·000575
3rd „ 1 to 8 „ . .	0·003996	0·000571
4th „ 1 to 9 „ . .	0·004619	0·000577
Mean		0·000574

Coefficient of elasticity, 7·94/·000574 = 13,830.

187. *Limit of Proportionality in Successive Loadings.*—If the limit of proportionality is not exceeded, its position is nearly stable in successive loadings. The following values were obtained in tests of a link from old Hammersmith Bridge :—

—	Extensions for six tons per sq. in.		
	First piece	Second piece	Second piece after three days
1st loading . .	·00344	·00346	·00341
2nd „ . .	·00345	·00343	·00342
3rd „ . .	·00342	·00347	·00340
4th „ . .	·00338	·00339	·00343
5th „ . .	—	—	·00342
6th „ . .	—	—	·00344
7th „ . .	—	—	·00343

If, however, the yield point is passed, the limit of elasticity very sensibly alters, as is shown in the following results deduced from Bauschinger's tables. A plotting of some of these is given in fig. 57 (§ 76).

ELASTIC LIMIT, IN TONS PER SQ. IN., IN BARS LOADED UP TO THE YIELD POINT

Material	Original state. First loading	Second loading	Third loading	Fourth loading
Bars loaded, unloaded, and reloaded immediately				
Weld iron . .	8·98	6·41	6·66	6·90
Ingot iron . .	15·78	—	4·01	4·12
,, . .	16·91	2·58	6·57	6·77
Copper . . .	2·45 [1]	3·59	3·92	5·11
Bronze . . .	3·43	4·06	4·13	—
Bars loaded, unloaded, and reloaded after a pause of 2½ to 80 hours				
Weld iron . .	8·98	12·94	15·84	17·45
,, . .	10·34	12·29	17·45	20·35
,, . .	10·22	14·22	15·78	18·94
,, . .	10·30	(6·57) [2]	18·80	(6·81) [2]
Ingot iron . .	15·09	5·13	7·92	6·83
Bessemer steel .	11·60	19·32	(3·91) [2]	6·69
Copper . . .	1·14 [1]	3·27	3·61	5·14
,, . . .	2·61 [1]	3·59	4·62	6·87
Bronze . . .	2·50	4·07	3·82	—
Bars loaded, unloaded, subjected to vibration, and reloaded after a pause				
Weld iron . .	12·38	11·93	14·89	11·14
,, . .	8·98	11·93	12·13	8·28
Ingot iron . .	15·15	5·18	5·26	5·39
,, . .	16·48	19·56	17·10	17·60

Bauschinger's tests indicate the following three laws: (*a*) If a bar is loaded above the limit of proportionality, but not beyond the yield point, the former is raised, even if the bar is reloaded immediately. (*b*) If a bar is loaded beyond the yield point, unloaded, and again loaded immediately, the limit of proportionality is found to be lowered, sometimes almost to zero. But if the reloading is done after an interval of time, the limit of proportionality is found to be raised; after a sufficiently long interval it may even be found to exceed the stress to which the bar was subjected. (*c*) When a bar is loaded beyond the yield point, unloaded, and reloaded, the yield point is raised up to the stress applied in the first loading, and this even if the reloading takes place immediately. If the bar is left at rest before reloading the yield point may be above the stress applied in the first loading.

188. *Determination of Elastic Limit by Change of Temperature.*—Suppose that a bar of unit length and section is

[1] Yield point not reached. [2] No pause between loadings.

subjected to a longitudinal stress p at absolute temperature T. If the deformation is purely elastic it will cool by the amount

$$-\Delta_T = \frac{T a}{m k}\Delta p \text{ degrees}$$

where a is the thermal coefficient of expansion, k the specific heat in mechanical units, and m the density of the material. But if the deformation is a permanent one, the equivalent of the work spent in internal friction will produce a heating effect. If the temperature of the rod is taken by thermo-couples during a test, the elastic limit is marked by a reversal of the temperature records. E. Rasch, of Gross Lichterfelde, states that the method is simple and reliable. He used silver-

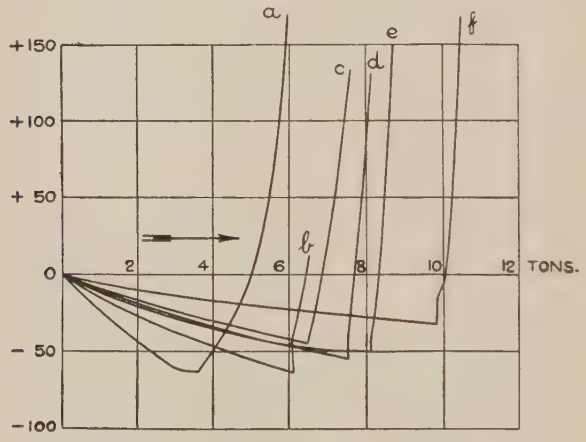


Fig. 163.

constantin, copper-constantin, and iron-constantin couples, consisting of wires 1 m. long and 0·5 mm. diameter, soldered with soft solder or silver. It is sufficient if the couple is pressed against the test bar by an india-rubber strap. The cold junctions clamped to wires leading to the galvanometer were placed in an oil tank. The test rod and junctions must be guarded against draughts.

Fig. 163 is a plotting of the results of tests on a brass rod. The curve a shows the relation of load and temperature as shown by galvanometer readings for the bar in its initial annealed condition. The galvanometer marks the elastic limit as a sharply defined minimum at 3·61 tons per sq. in. The other curves mark in the same way well-defined inflections at the elastic limit (or perhaps yield point) in successive loadings.

189. *Poisson's Ratio.*—When a bar is subjected to a simple axial longitudinal stress not exceeding the elastic limit, it extends in length and contracts laterally, or contracts longitudinally and expands laterally. If $\pm \lambda$ in the longitudinal and $\mp \lambda/m$ the lateral deformation reckoned per unit length, then $1/m$ is termed Poisson's ratio.

Bauschinger found by direct measurements of the longitudinal and transverse dimensions of bars subjected to tension and compression the following values: For cast iron in compression, m decreased from about 4 for small stresses ($\frac{1}{2}$ ton per sq. in.) to 2·8 for large stresses (36 tons per sq. in.). In tension the value ranged from 6 to 5. For forged iron in compression $m = 4{\cdot}5$ to $3{\cdot}7$; for rolled iron $m = 3{\cdot}3$ to $3{\cdot}1$. For axle steel $m = 4{\cdot}2$ to $3{\cdot}4$. For boiler plate $m = 3{\cdot}7$. For sandstone in compression the value of m decreased from 12 for very small stresses to 4 for very large stresses. For iron and steel, when the elastic limit (yield point) was passed, the value of m sank to 2·2 to 1·7.

Mr. Stromeyer has also carried out direct measurements of Poisson's ratio. For ordinary steel and iron he found $m = 3{\cdot}66$ to $3{\cdot}32$. For cast iron $m = 6{\cdot}76$ to $3{\cdot}72$. For rolled copper $m = 3{\cdot}12$. For cast copper $m = 2{\cdot}73$ to $2{\cdot}63$. For bronze $m = 3{\cdot}28$ to $3{\cdot}09$. For manganese bronze $m = 2{\cdot}93$. For Delta metal $m = 1{\cdot}85$. For Muntz metal $m = 3{\cdot}53$ to $2{\cdot}80$. Mr. Stromeyer concludes that Poisson's ratio has not a constant value for different materials, and that its value found by direct measurement differs from that deduced from values of C and E obtained in torsion and tension tests.

The following table gives values of Poisson's ratio $1/m$ from various authorities:

POISSON'S RATIO.[1]

Material	Wertheim	Bauschinger	Stromeyer	Morrow
Glass	·25	—	—	—
Mild Steel	·27	·29	·27 to ·30	·27 to ·28
Wrought Iron	—	·26 to ·31	·28 to ·30	·27 to ·29
Brass	·33	—	·28 to ·36	·32 to ·35
Copper	·33	—	·33	·31 to ·34
Cast Iron (tension)	—	·16 to ·19	·15 to ·27	·23 to ·27
(compression)	—	·32 to ·38	—	—
Lead	·43	—	—	—

[1] Bauschinger, *Civilingenieur*, xxv. 81. Stromeyer, *Proc. Roy. Soc.*, lv. 373. Morrow, *Proc. Phys. Soc.*, xviii. 582.

CHAPTER XIII

CAST IRON

Cast iron produced in the smelting furnace is a material the properties and uses of which place it in a class apart. It is not usefully malleable at any temperature.

190. *Constituents of Cast Iron.*—Cast iron consists of iron mixed or combined with carbon, silicon, manganese, sulphur, and phosphorus. Popularly, and with partial truth, the carbon is regarded as chiefly determining its characteristics. The carbon exists in cast iron either combined with the iron or mixed with it in the form of graphite. The greyer irons contain most graphitic carbon, and are weaker, more fusible, and softer than whiter iron; the white iron contains most combined carbon. The other constituents have an influence on the condition in which the carbon is found in the iron, and therefore indirectly influence the mechanical properties. The composition of cast iron varies within the following limits, if extreme qualities, unsuited for foundry use, are excluded:

	Per cent.	Per cent.
Combined carbon	·15 to 1·25	2·0 to 4·5
Graphite	1·85 „ 3·25	
Silicon		0·15 „ 5·0
Sulphur		0·0 „ 0·5
Phosphorus		0·0 „ 1·3
Manganese		0·0 „ 1·5
Iron		90·0 „ 95·0

Aluminium and silicon hinder the combination of carbon with the iron, cause the separation of graphite, and render it greyer. Manganese and chromium have a reverse effect.

In some cases silicon is now added to cast iron to improve its working properties. Ferro-silicon, a cast iron with 10 per cent. of silicon, is used to mix with other cast iron[1] to render

[1] See papers by Mr. Thomas Turner: 'On the Influence of Silicon on the Properties of Cast Iron,' *Journal of Chemical Society*, August 1885, December 1885, and March 1886. 'On the Influence of Remelting,' *ibid.*, July 1886. 'The Constituents of Cast Iron,' *Journal of the Iron and Steel Institute*. Ferd.

it greyer, stronger, and more suitable for foundry purposes. The softest iron used in the foundry has about 0·15 per cent. of combined carbon. With 0·7 per cent. the transverse strength is greatest; with more the crushing strength increases, but the tenacity and transverse strength diminish. The amount of graphitic carbon has less influence. The silicon, when it does not exceed 2½ per cent., appears to be advantageous in securing a soft, grey, strong iron. Manganese in small quantity appears to be advantageous, but when it exceeds one per cent. the iron becomes white, and weak except for crushing. Sulphur should not exceed 0·15 per cent. Phosphorus in small quantity renders the iron fluid, and suitable for very thin castings, but it renders the metal brittle. Remelting cast iron improves its strength, but if the remelting is repeated too long the tensile and transverse strength suffer, though the crushing strength and hardness increase. This change of properties is connected with a change of the iron from grey to white by increase of combined carbon and decrease of silicon. The following analyses, by M. Gauthier, show the kind of change which occurs in remelting:

—	Original pig	Fourth melting	Sixth melting
Graphite	2·73	2·54	2·08
Combined carbon . .	0·66	0·80	1·28
Silicon	2·42	1·88	1·16

In Mr. Turner's very valuable paper (*Trans. Iron and Steel Institute*, 1885) an attempt is made, from an examination of all existing data, to determine the best composition of cast iron to obtain certain definite qualities. From this the following table of percentages is compiled:

—	Combined carbon	Graphitic carbon	Silicon
Greatest softness . .	0·15	3·1	2·5
„ hardness . .	—	—	under 0·8
„ general strength	0·50	2·8	1·42
„ stiffness . .	—	—	1·0
„ tensile strength .	0·47	—	1·8
„ crushing „ .	over 1·0	under 2·6	about 0·8
„ transverse „ .	0·7	—	1·5

Gauthier, of Paris, 'On Silicon in Foundry Iron,' *Journal of Iron and Steel Institute*, 1886. Turner, 'The Metallurgy of Iron,' *Griffin*, 1895. Keep, *Trans. Am. Soc. Mech. Eng.*, vol. vi. 1865.

The density varies with the composition in the following way:

Material	Density	Weight of a cubic foot in lbs.
Dark grey foundry iron . . .	6·80	425
Grey „ „ . . .	7·20	450
Mottled „ „ . . .	7·35	458
White iron	7·60	474

The specific heat is 0·140 for grey iron, and 0·127 for white iron. Cast iron melts at about 2,732° F.

191. *Mechanical Properties of Cast Iron.*—The elastic properties of cast iron have already been discussed. In tension and compression tests there is strictly no range of stress for which the stresses and strains are proportional, and there is no fixed coefficient of elasticity or elastic limit. It has, however, already been shown that the extensions and compressions are nearly the same for equal stresses (§ 44).

Hodgkinson found that the relation of stress and strain in cast iron was given very nearly by the following equations. Let p be the stress in tons per sq. in., e the extension, and c the compression per unit of length. Then—

$$p = 6{,}220\, e = 1{,}298{,}000\, e^2$$
$$= 5{,}773\, c = 233{,}500\, c^2.$$

The author has found the following inverse relations still more exact:

$$e = 1{\cdot}503\, p^3 \times 10^{-6} + 1{\cdot}685\, p \times 13^{-4},$$
$$c = 9{\cdot}66\, p^3 \times 10^{-8} + 1{\cdot}782\, p \times 10^{-4}.$$

These are from experiments on very long bars. For 8-inch bars—

$$e = 0{\cdot}39\, p^3 \times 10^{-6} + 1{\cdot}62\, p \times 10^{-4}.$$

The following table gives a few measurements of extension in short cast-iron bars. The cast iron was the ordinary mixture of a good foundry:

EXTENSIONS OF CAST-IRON BARS

(Extensions in 8 ins., measured by touch micrometer. Bars screwed at ends and fixed in nuts with spherical seatings)

Load in tons	Diam. 1·0005 Area ·7862	1·005 ·7862	·999 ·7832	1·000 ·7854	·999 ·7832	·993 ·7743
	Extensions per ton in 8 ins., in inches					
2·5	·00172	·00144	·00136	·00148	·00156	·00136
4·5	·00162	·00153	·00138	·00153	·00165	·00136
5·5	·00169	·00158	·00145	·00162	·00175	·00151
6·5	·00175	·00165	·00162	·00172	·00178	·00160
7·5	·00185	·00176	·00178	·00189	·00196	·00175
8·5	·00196	—	—	—	—	—
9·5	·00226	—	—	—	—	—
Breaking weight in tons per sq. in.	12·94	14·37	13·87	13·04	14·21	13·90

192. *Ultimate Tensile Strength of Cast Iron.*—In making and in comparing tensile tests the following points must be kept in mind. A few not entirely satisfactory experiments show that in small castings the strength varies a good deal with the size, the smaller castings being stronger. Hodgkinson found test bars of 1, 2, and 3 sq. ins. section to have tenacities proportional to 100, 80, and 77. The form of the test bar has less influence. Hodgkinson found that bars of cruciform section were about 1 per cent. stronger than bars with circular or rectangular sections of the same area. Tensile tests are most commonly made on rough bars with the skin on, and there is a popular impression that it weakens a bar to take off the skin. This is almost certainly erroneous, and, as accurate measurements cannot be made on a rough bar, the test bars ought to be turned. Tensile tests should be made with shackles having spherical seats, as cast iron is greatly weakened by non-axiality of the stress. Some of the low tensile strengths found in the older experiments are probably due to neglect of proper conditions in holding the test bars in the shackles. In very careful tests the test bars should be cast in one with the work for which the cast iron is used, and not separately. They can be broken off, and turned to the required form. Mr. Oughterbridge has shown that, if cast-iron test bars are subjected to vibration in a tumbling barrel or by hammering, they gain 10 to 15 per cent. in strength from relief of internal stresses.

The table on the following page gives a summary of the most trustworthy results of tensile tests.

TENACITY OF CAST IRON

Experimenter	No. of tests	Section of bars in sq. in.	Tenacity in tons per sq. in.			Probable No. of fusion	Condition of test bars	—
			Highest	Lowest	Mean			
Minard and Desormes	13	0·23 to 0·5	9·08	5·09	7·19	—	Rough	1815. Love. 'Résistance de la Fonte'
Hodgkinson and Fairbairn	—	1 to 4	9·76	6·00	7·37	2nd	Rough	1837. 'Brit. Assoc. Rep.' VI.
Hodgkinson and Fairbairn	81	3 to 4½	10·5	4·9	6·83	2nd	Rough	1849. 'Report on App. Iron'
Woolwich	53	—	15·3	4·2	10·4	2nd and 3rd	?	1856. Report of 1858
Wade	6	—	—	—	13·7 [1]	—	—	1856. 'Report on Metal for Cannon'
„	4	—	—	—	9·1 [2]	—	—	1856. 'Report on Metal for Cannon'
Turner [3]	—	1·0	15·7	4·75	—	2nd	Rough	1885. 'Journ. of Chem. Soc.'
Rosebank Foundry	23	—	18·2	6·5	15·3 [4]	—	—	'Industries,' April 1887
Unwin	6	0·75	—	—	13·7	2nd	Turned	—
„	3	1·0	17·3	14·9	15·7	2nd	Turned	—
Wade	—	—	20·5 [5]	—	—	—	—	—

[1] Selected as good iron. [2] Selected as bad iron.
[3] Special series of experimental test bars, with varying proportion of silicon.
[4] Mean of ten best specimens. [5] Highest result obtained.

Strength of Cast Iron at Different Temperatures.—Cast iron loses little of its strength up to 400° C. Taking the strength at ordinary temperatures, Bach and Rudeloff found the relative strength at higher temperatures to be as follows:

Temperature, C. . .	20	300	400	500	600
Relative Strength					
Bach	100	99	92	76	52
Rudeloff . . .	100	88	107	68	38

The tensile strength of the cast iron used by Bach was about 14½ tons per sq. in., and that of the cast iron used by Rudeloff about 8½ tons per sq. in. at ordinary temperature.

193. *Crushing Strength of Cast Iron.*—Hodgkinson used for compressive tests small cylinders and square and triangular prisms, having heights equal to from one to three times the transverse dimensions. He placed a sheet of lead on the faces of the prisms. It is not clear that this may not have diminished the strength. The most common form of fracture is shearing at an oblique plane making an angle of about 56° with the axis.

The crushing resistance is much increased if the height is so decreased that the plane of least resistance to shear cuts the faces at which the pressure is applied. The following results were obtained by Hodgkinson on cylinders ½ inch in diameter:

Height of cylinder in in.	⅛	¼	⅜	½	¾	1½	2	3¾
Crushing strength in tons per sq. in.	69·3	63·5	60·0	55·0	53·3	53·3	49·6	34·4

The strength is pretty uniform if the height is between one and three diameters.

194. *Transverse Strength of Cast Iron.*—Tests by cross-breaking are so easily made that this kind of test has been very generally adopted as the commercial test for cast iron. Rectangular bars of 1″ × 1″ cross-section, or more commonly of 2″ × 1″ cross-section, are cast, and these are placed on supports and loaded at the centre.

Within the elastic limit, the relation between the bending moment M and the stress in the bar f is given by the equation $M = f z$, where z is the modulus of the section. For a rectangular bar of breadth b, depth d, span l, all in inches, loaded at the centre with W tons and supported at the ends—

CRUSHING RESISTANCE OF CAST IRON

Authority	Form of test piece	Transverse dimensions in inches	Height / Width	No. of tests	Crushing strength in tons per sq. in.			—
					Highest	Lowest	Mean	
Hodgkinson .	Cylinders and prisms	$\frac{1}{4}$ to $\frac{3}{5}$	1 to 3	—	64·9	36·5	48·0	'Brit. Assoc. Rep.' v. VI. 1837
,, .	Cylinders	$\frac{3}{4}$	1 to 2	81	53·8	24·7	38·5	'Com. on App. of Iron,' 1849
Woolwich .	Cylinders	0·6	2	273	62·5	19·8	40·6	Report, 1858
Wade . .	—	—	—	—	74·5	44·6	—	Thurston, 'Materials of Construction'
Turner . .	Cylinders	0·75	3	11	92·5	34·1 [1]	—	'Journ. of Chem. Soc.' 1885
Fairbairn .	—	—	—	—	95·9 [2]	—	—	—

[1] Series of special test bars, with varying percentage of silicon.
[2] Highest result after repeated remeltings.

$$f = \frac{3\,\mathrm{w}\,l}{2\,b\,d^2} \text{ tons per sq. in.}$$

For b =	d =	l =	f/w =
1	1	24	36
1	1	36	54
1	2	24	9
1	2	36	13½
1	2	40	15

If in this equation the breaking weight w_b is put for w, the value f_b found for f is no longer the real stress in the bar, and varies for the same material with the form of the section. The value f_b so found may be termed the *coefficient of breaking strength*. For bars of similar form of section it is taken as a measure of the quality of the material.

Let f_t be the tenacity found by a tension test, and f_b the coefficient of breaking strength for the same iron from a transverse test. Then Bach has found that

$$f_b = \mu f_t \sqrt{\frac{y}{z}}.$$

z is the modulus of the section, and y the distance from the neutral axis to the edge of the section in tension. μ is a constant = 1·2 for sections with straight edges (as rectangles and **I** sections) and = 1·33 for sections with curved edges.

Even when the section is rectangular the proportions of the section affect the coefficient f_b, and for bars of the same proportions the coefficient is lower as the section is larger. The values of the coefficient, given in the following table, have been calculated from comparable series of experiments :

Coefficient of Bending Strength, f_b, for Rectangular Bars

Authority		Dimensions of bars in inches b	d	l	Centre breaking weight, in tons W_b	f_b, in tons per sq. in.	—
Clark, E.	1	1	1	54	0·252	20·41	D. K. Clark, 'Rules,' &c. p. 562
,,	2	1	3	216	0·429	15·45	
,,	3	3	1	27	1·376	18·58	
,,	4	2	2	162	0·475	14·43	
,,	5	2	3	108	1·800	16·20	
,,	6	3	2	54	2·410	16·27	
,,	7	3	3	162	1·436	12·92	
Millar	1	1	2	36	1·67	22·6	'Proc. I. C. E.' lviii. p. 222
,,	2	1	1	31	0·358	19·6	
,,	3	2	1	36[1]	0·785	21·3	
Segundo and Robinson[2]	1	0·9	2·93	20	4·82	18·75	'Proc. I. C. E.' lxxxvi. p. 248
	2	2·93	0·9	20	1·50	19·05	
	3	2 in.	diam.	20	3·35	24·28	

[1] Single experiment.

[2] These bars were planed or turned.

It will be seen that, generally, a wide bar gives a higher, and a deep bar a lower coefficient. Comparing Clark's results 1, 4, and 7, and again Millar's 1 and 2, the coefficient decreases as the section is larger. The circular section has a higher coefficient than the rectangular. The actual tenacity of the iron of Mr. Millar's bars, determined from 66 tests, was 9·45 tons per sq. in. That of Messrs. Robinson and Segundo's bars was 11·06 tons per sq. in. It is obvious, therefore, that the coefficient of bending strength for such bars differs widely from the tenacity, as has indeed long been known.

The ultimate deflection is often noted in transverse tests of cast iron as an index of the softness of the iron. From various tests on bars of different depth and span, the ultimate deflection is on the average—

$$\delta = 0{\cdot}000025 \frac{l^2}{d} f_b.$$

According to Mr. Millar, tapping a bar with a hammer during test reduces its strength. Mr. Millar found no difference of strength in planed bars and rough bars with the skin on. Messrs. Segundo and Robinson found the rough bars to be somewhat stronger than the planed bars. Mr. Millar found that bars run with hot metal were a little weaker and deflected a little more than bars run with dull metal.

Coefficient of Bending Strength for Cast-iron Bars

Authority	Dimensions of bars in inches b d l	No. of tests	Coefficient f_b in tons per sq. in.		
			Highest	Lowest	Mean
Fairbairn & Hodgkinson	1 × 1 × 54	270	21·0	12·9	16·3
Woolwich . . .	2 × 2 × 20	564	30·0	6·9	18·9
Millar	1 × 2 × 36	1,344	—	—	22·6
„	1 × 1 × 36	50	—	—	19·6
Stephenson . . .	—	—	25·6	16·5	—
Turner, 1886 . . .	—	—	28·3[1]	—	—

For the ordinary test bar, 3 feet span, 2 inches deep, and 1 inch wide, the central breaking weight varies for different qualities of iron from 10 to 42 cwts. Common iron ought to carry 20 cwts., good iron 30 cwts., and Mr. Turner states that iron carrying 40 cwts. can be produced with tolerable

[1] Maximum of special series of test bars.

regularity if necessary. The most common tests imposed in specifications vary from 25 to 32 cwts. It is usual to take the average breaking weight of the bars of each cast, as from flaws, cold shots, &c., individual bars vary a good deal.

195. *Resistance of Cast Iron to Shearing.*—The resistance of cast iron to shearing is imperfectly known. Mr. Stoney found a resistance of 8 to 9 tons per sq. in. The following results are from a paper by Messrs. Platt and Hayward,[1] the experiments having been made at University College. The cast iron had a tenacity of about 11·4 tons per sq. in. The specimens were about $\frac{3}{4}$ inch in diameter:

Material	No. of tests	Shearing strength in tons per sq. in.
Cast iron No. 1, turned . .	13	5·29
„ No. 2, „ . .	12	5·08
„ No. 2, skin on . .	7	3·92

It is extremely difficult in shearing experiments to ensure a uniform distribution of stress on the section.

Mr. Izod (*Proc. Inst. Mech. Eng.*, 1905) has obtained the following values for the shearing resistance of cast iron:

Material	Tensile strength in tons per sq. in.	Shearing strength in tons per sq. in.
Cast Iron, A	9·7	14·8
„ B	13·4	17·4
„ C	11·3	13·9
„ D	13·7	16·1
„ E	13·5	14·8

196. *Resistance of Cast Iron to Torsion.*—The ordinary expression for resistance to torsion is $T = fz$, where T is the twisting moment, z the polar modulus of the section, and f the shearing stress in the most strained layer. For a circular section of diameter d this becomes—

$$T = 0{\cdot}196\, f d^3.$$

When T is the twisting moment which breaks the bar, this expression becomes an empirical one, and f then has values greater than the real shearing stress, just as in the case of bending. It is better to call the values of f which correspond to the breaking twisting moment coefficients of torsional strength.

[1] *Proc. Inst. Civil Eng.*, xc. 382.

Experiments by Messrs. Platt and Hayward, on the same cast iron as that used in their experiments on shear, gave the following results. The bars were about $\frac{5}{8}$ inch in diameter. Some Woolwich results on 276 specimens of cast iron 1·8 inch in diameter are also given, and some American results:

Material	Coefficient of torsional strength, f	Coefficient of rigidity, C	Authority
	Tons per sq. in.	Tons per sq. in.	
Cast iron, No. 1, turned .	15·9	3,197	Platt and Hayward
„ „ skin on .	18·1	3,402	
„ No. 2, turned .	17·1	2,947	
„ „ skin on .	15·3	3,147	
„ highest . .	22·0	—	Woolwich
„ lowest . .	8·25	—	
„ mean . .	13·5	—	
„ highest . .	23·5	—	American
„ lowest . .	12·5	—	

MALLEABLE CAST IRON

197. Malleable cast iron is obtained by heating castings to red heat in contact with hematite iron ore, for a period varying from some hours to two or three days. The amount of carbon in the cast iron diminishes, and it becomes to a certain extent malleable and capable of being bent or hammered.

The following tests were made by Professor P. C. Ricketts, at the Rensselaer Polytechnic Institute (*Van Nostrand's Magazine*, 1885). The cast iron had a tenacity ranging from 6·5 to 13·1 tons per sq. in., the mean tenacity being 10·1 tons per sq. in. The elastic limit given appears to be the yield point. The extension was measured in a length of 5 inches to 10 inches.

TENSILE STRENGTH OF MALLEABLE CAST IRON

Form of bars	Approximate size	Mean elastic limit in tons per sq. in.	Tenacity in tons per sq. in.			Elongation per cent.	Contraction per cent.
			Highest	Lowest	Mean		
Square . 1–8	$\frac{3}{4} \times \frac{3}{4}$	0·45	19·7	16·1	17·8	5·6	6·9
„ . 11–14	„	1·01	—	—	14·5	2·0	4·7
Rectangular 1–7	$1 \times \frac{3}{8}$	1·33	16·5	14·6	15·3	2·4	6·6
Circular . 1–9	$\frac{1}{2}$ diam.	1·02	19·8	16·1	17·4	3·5	10·0
„ . 1–13	$\frac{3}{4}$ „	0·65	18·2	12·8	15·2	1·7	4·3
„ . 1–8	$\frac{3}{4}$ „	—	—	—	13·4[1]	0·8	3·5

[1] Skin turned off.

Short prisms and cylinders carried loads of from 48 to 71·5 tons per sq. in. before crushing. In bars broken by bending the coefficient of bending strength varied from 20 to 40 tons per sq. in. Martens [1] found the ultimate tensile strength of malleable cast iron to be 16·4 tons per sq. in.; contraction, 8·2 per cent.; extension in 8 inches, 2·5 per cent.; limit of elasticity, about 4·4 tons per sq. in.

[1] *Mitt. a. d. K. Techn. Versuchsanstalten zu Berlin*, 1886, p. 131. See also Stanford, *Trans. Am. Soc. Civil Eng.*, 1895.

CHAPTER XIV

IRON AND STEEL

198. Down to a recent period the ferrous materials used in construction could be divided into three groups, marked equally by difference of manufacture, of chemical composition, and of mechanical properties. Cast iron, the product of the blast furnace; wrought iron, the product of the puddling forge; and steel, produced from wrought iron by cementation had characteristics so marked that it mattered little which of their differences was taken as a basis of classification. As their content of carbon seemed essentially connected with their properties, that was generally selected as a means of discrimination.

The matter is no longer so simple. As to cast iron, no difficulty arises; its method of production, its properties, and its engineering uses place it in a class apart. Wrought iron, produced in the puddling forge, though for most constructive work superseded by so-called steel, has distinctive qualities which ensure its use for limited purposes. It is as to so-called steel that confusion arises. Down to 1856, steel, whether produced by cementation or in the crucible, was a material possessing the characteristic property of hardening when suddenly cooled. Since the development of the Bessemer and Siemens-Martin processes, a new material has been produced, commonly called steel, but which differs from the older material of that name. The plates and bars of steel, which have superseded wrought iron in construction, contain carbon, but in quantities varying without break from a percentage as small as that in wrought iron to a percentage as high as that in cementation steel. Such material varies in tenacity from that of wrought iron to a tenacity at least double that of wrought iron. Lastly, by far the larger part of this new material has not the characteristic property of the older steels of hardening when suddenly cooled.

There is a difference between wrought iron and the new

material which is replacing it, important enough to justify a difference of classification. Wrought iron, and cementation steel as made from wrought iron, have been in the condition in the puddler's forge of granular or spongy masses bathed with liquid slag. This slag is never entirely got rid of, and remains in the forged material, not in great quantity indeed, but so distributed as to give rise to a visible structure. Bessemer, Siemens-Martin and crucible steel, on the other hand, have all been fused and more perfectly cleared of mechanically mixed impurity. They have, when rolled, a homogeneousness and absence of grain which is definite and important. If the difference between puddled and cast material is recognised, it will be found that there are two parallel series of products, first clearly arranged by M. Greiner, of Seraing:

Percentage of Carbon			
0·0 to 0·15	0·15 to 0·45	0·45 to 0·55	0·55 to 1·5
Series of the Irons			
Ordinary iron	Granular iron	Puddled steel	Cemented steel
Series of the Steels			
Extra soft steel	Soft steel	Medium steel	Hard steel

This classification ignores the property of tempering as a mark of distinction between iron and steel, which is in some respects inconvenient. Hence, in Germany, it is becoming common to class one series as a weld metal, the other as ingot metal. *Weld iron* and *ingot iron* are those materials which will not temper; *weld steel* and *ingot steel,* those which harden when suddenly cooled. *Cast steel* originally meant crucible steel, but the term is ambiguous, as it is sometimes applied to steel castings, which have not been forged or rolled.

I. Influence of Chemical Composition on the Mechanical Properties

199. *Weld Iron.*—Wrought iron, the product of the puddling forge, should contain not less than 99 per cent. of iron, and is softer, more ductile, and more valuable the

purer it is. The small percentage of carbon found in all commercial iron increases its strength. Sulphur and phosphorus are prejudicial, the former making it brittle when hot and difficult to roll or weld, the latter making it brittle when cold.

Ingot Iron and Steel.—Mild steel is made from pig iron by the Bessemer acid, the Bessemer basic, the open hearth acid, and the open hearth basic processes. In the acid processes the phosphorus in the pig iron remains in the finished product, and therefore pure qualities of pig iron must be used. In the basic process much of the phosphorus is eliminated and less pure qualities of pig can be used. In Great Britain, the open hearth acid process is chiefly adopted in making plates. For rails and bars the three first named processes are used. In the United States, the first, third, and fourth processes are employed in the manufacture of plates, and the first for rails. In Germany, the Bessemer basic process is largely used.

200. *Constituents of Ingot Iron and Steel.*—In consequence of the homogeneousness due to fusion in manufacture, ingot iron is more ductile than weld iron containing the same proportion of carbon. The low basic steel, which is the purest commercially produced ingot metal, is the most ductile. In proportion as other constituents are added to the iron, the strength increases and the ductility diminishes. But the influence of such ingredients is complicated and at present imperfectly understood. Carbon, up to 1·2 per cent., causes the steel to be harder, stronger, less ductile, and when it exceeds about 0·5 per cent. confers the property of tempering or hardening by sudden cooling. It may be present in steel in proportions up to 1·5 per cent. Manganese appears to be necessary in steel-making to remove silica and iron oxide in the molten metal. Part remains in the steel, and acts in the same way as carbon. Where strength and toughness are required, they are more safely obtained by carbon and manganese than by the former alone. Ordinary steel contains 0·25 to 1 per cent. of manganese. A remarkable alloy has been obtained by Mr. Hadfield, containing 14 per cent. of manganese and 1 per cent. of carbon, which is remarkably strong and tough, and forges well, but is too hard to be worked cold. It is practically non-magnetic. Phosphorus acts like carbon, but it makes the steel brittle when cold (cold-short) and its presence, except in minute

proportion, is injurious. Silicon is used in making steel castings to reduce the temperature of fusion and to prevent blowholes. Tungsten and chromium act like carbon, but more energetically, and have been used in making steel of great hardness. Nickel, in proportions up to 7 per cent., increases the elastic limit and tensile strength. Aluminium lowers the melting point, and is useful in making sound castings. Sulphur makes steel brittle when hot and diminishes its weldability.

STEEL FOR DIFFERENT PURPOSES

Per cent. of carbon	
0·15 to 0·30	Boiler tubes
0·00 „ 0·10	Telephone and telegraph wires
0·10 „ 0·35	Ordinary wire ropes
0·45 „ 0·75	Special wire rope of hardened wire
0·50 „ 0·75	Springs
0·90 „ 1·00	Surgical knives
0·80 „ 0·90	Ordinary saws
0·70 „ 0·85	Chisels for cold iron
1·00 „ 0·20	Cutters, drills, &c.
1·20 „ 1·40	Turning, planing tools, &c.

It is beyond the purpose of this work to give detailed analyses of steel, but the following short summary is a guide to the ordinary composition of these materials :

—	Per cent					
	Carbon	Manganese	Silicon	Sulphur	Phosphorus	Iron
Wrought Iron .	0·02–0·25	0–0·3	0–0·2	0–0·015	0–0·15	99–99·5
Steel:						
Tyres . .	·24–·63	·21–1·0	·16–·33	·01–·09	·04–·05	98·74
Rails . .	·35–·60	·50–1·0	·04–·10	·07–·14	·03–·07	98·44
Mild plates .	·115	·504	·055	·028	·037	99·35
Med.-hard do.	·33	1·008	·065	·022	·075	98·40

Table I., selected from various tests, gives the correspondence between the mechanical properties and the chemical composition.

201. *Influence of the Amount of Carbon in Steel on its Strength and Ductility.*—In steel as commercially made the percentage of carbon affects the mechanical properties in the most significant way. Up to about 1·2 per cent. the strength is increased and the ultimate elongation diminished with

TABLE I. STEEL. CORRESPONDENCE OF MECHANICAL PROPERTIES AND COMPOSITION

Kind of steel	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Elastic strength, tons per sq. in. f_y	Tensile strength, tons per sq. in. f_t	Elongation per cent. 100 λ
Boiler-plates	·19	·63	·05	—	—	18	28·5	32 in 4″
,, (loco. shell) . .	·25	·45	·05	·05	·05	—	25 to 29	26 ,, 8″
,, (loco. firebox) .	·25	·45	·03	·04	·03	—	25 ,, 29	28 ,, 8″
Angle and channel bars . .	·2 to ·25	·5 to ·6	·04	—	—	—	27 ,, 30	30 ,, 4″
Forgings . . . . from	·3	·75	·03		—	21	35	16 ,, 4″
,, ... to	·4	1·0	·04		—	—	45	25 ,, 4″
,, (for guns) . . from	·24	·5	·03	·02	·06	—	37	30 ,, 2″
,, ... to	·34	·9	·05	·03	·10	—	42	22 ,, 2″
,, (loco. and carriage axles)	·27	1·0	·04		-	19 to 21	30 to 32	26 ,, 4″
Spring steel . . . soft	·45	1·0	·05	-	—	—	46	21 ,, 4″
,, . . tempered	—	—	—	-	—	—	70	3 ,, 8″
Rails . . . . . from	·3	·5	·05	·05	·01	19	35	22 ,, 8″
,, ... to	·5	1·1	·10	·09	·20	28	50	12 ,, 8″
Steel castings . . . from	·15	·4	·02	-	·25	- -	25	30 ,, 4″
,, ... to	·40	·7	·08	—	·50	-	35	12 ,, 4″

increasing percentage of carbon. Beyond that limit both the strength and ductility diminish. Table II. gives results from

Table II. Swedish Steel from Surahammar (Styffe)

Material	Mark	Percentage of carbon, C	Breaking strength, in tons per sq. in. *ft*
Puddled steel .	NP. 1	0·8	49·9
„ „ .	B. 1	0·8	40·5
„ „ .	NP. 2	0·7	37·6
„ „ .	NH. 1	0·7	37·3
„ „ .	NH. 2	0·7	37·4
„ „ .	G. 2	0·7	35·0
„ „ .	P. 1	0·6	32·8
„ „ .	P. 2	0·6	36·7
„ „ .	B. 2	0·55	38·8
„ „ .	B. 3	0·5	31·7
„ „ .	G. 2	0·5	35·0
Iron . . .	B. Iron	0·2	21·5

Styffe on steel made at Surahammar. Table III. gives results obtained by Bauschinger on steel made at the Ternitz Works ('Mittheilungen, München, IV.' 1874). For tension, plates 24 ins. long, 2·8 ins. wide, and 0·48 in. thick were used. For compression, prisms 3·6 ins. long and 1·2 × 1·2 in. in section were used. The shearing test bars were 6 ins. long, 2·8 ins.

Table IV. Experimentally Prepared Steels, Tested by Professor J. O. Arnold at Sheffield

Condition	Per cent. of carbon, C	Elastic limit, tons per sq. in. f_y	Maximum stress, tons per sq. in. *ft*	Elongation per cent. 100λ	Contraction of area, per cent.
N	0·08	12·19	21·39	46·6	74·8
A	„	8·82	18·34	52·7	76·7
N	0·21	17·08	25·39	42·1	67·8
A	„	9·02	21·25	42·3	65·7
N	0·38	17·95	29·94	34·5	56·3
A	„	9·55	25·02	35·0	50·6
N	0·59	19·82	42·82	19·9	22·7
A	„	11·36	31·87	22·0	23·3
N	0·89	24·80	52·40	13·0	15·4
A	„	16·81	36·69	4·5	4·2
N	1·20	35·72	61·65	8·0	7·8
A	„	16·19	32·87	6·0	4·9
N	1·47	32·27	55·71	2·8	3·3
A	„	10·08	22·33	19·0	17·7

wide, and 0·4 in. thick. Table IV. gives results on specially prepared steel with great variation in the proportion of carbon,

TABLE III. STEEL FROM THE TERNITZ STEEL WORKS

Percentage of carbon, C	Mean coefficient of elasticity in tension within elastic limit, tons per sq. in. E	Strength at limit of elasticity in tension, tons per sq. in. f_y	Breaking tensile strength, tons per sq. in. f_t	Elongation in 16 in. per cent. 100 λ	Contraction of area per cent.	Coefficient of elasticity in compression, in tons per sq. in. E	Limit of elasticity in compression, in tons per sq. in. f_c	Ultimate shearing resistance, in tons per sq. in.
·14	14,300	18·73	28·1	21·8	49·2	17,080	17·65	21·7
·19	13,780	21·02	30·4	20·1	41·7	16,580	19·20	23·6
·46	14,300	21·90	33·8	18·1	30·5	14,660	21·85	22·8
·51	14,040	21·62	35·6	14·3	25·1	14,540	20·64	25·5
·54	13,720	22·15	35·3	17·8	32·8	16,130	21·85	25·0
·55	14,100	20·98	35·9	17·6	27·9	15,040	22·22	25·4
·57	13,720	21·02	35·6	18·4	30·7	14,280	21·85	23·1
·66	14,480	23·77	40·0	13·7	19·7	15,940	23·95	27·2
·78	14,980	23·80	41·1	11·4	19·1	14,480	23·95	26·3
·80	13,660	25·45	45·9	9·0	14·0	14,480	28·20	30·6
·87	13,900	27·24	46·7	8·1	16·5	14,100	25·00	31·7
·96	13,820	30·90	52·7	6·6	10·0	14,600	31·75	37·0

tested by J. O. Arnold (*Proc. Inst. Civil Engineers*, cxxiii. p. 127). In these tests two series, normal and annealed, were used. The normal specimens had been heated to 1,000° C. and cooled in air. The annealed specimens had been similarly heated in quicklime for seventy-two hours and cooled in the furnace during 100 hours. The test bars were 0·564 inch diameter for a length of 2 inches. N and A indicate normal and annealed condition. Table V. gives some results on gun steel tested after oil tempering ('Treatise on Service Ordnance,' 1893, p. 448).

Table V. Steel used in the Manufacture of Ordnance, Oil Tempered

Series	Carbon per cent. C	Manganese per cent.	Elastic limit (yield point), tons per sq. in. f_y	Testile strength, tons per sq. in. f_t	Elongation in 2 in. per cent. 100 λ	Ratio $\frac{f_y}{f_t}$
A	·153	?	21	32	31·9	·74
B	·148	·523	24	36	27·4	·73
C	·228	·380	26	39	28·4	·73
D	·244	?	27	41	22·4	·74
E	·351	?	32	48	18·0	·73
F	·448	?	38	56	13·8	·72
G	·502	?	43	62	12·5	·71
H	·646	·379	50	71	10·2	·70

II. Influence of Differences of Mechanical Treatment in Manufacture and Testing

202. *Interpretation of Observations in a Tensile Test of Ductile Material.*—It is desirable to consider what deductions can be made from the observations in a tensile test, without at present considering what results are commercially used as tests of quality.

The table following gives observations in a tensile test of Lowmoor plate. The maximum stress is 23·2 tons per sq. in. of initial section. Beyond this stress the load was reduced to balance the molecular forces. As the loading increased the section diminished, and, on the principle stated (§ 26), the area of the reduced section can be calculated. If ω is the section when the length is l, and ω_1 the section when the length is $l + e$, then $\omega l = \omega_1 (l + e)$ and $\omega_1 = \omega l / (l + e)$. The real stress on the reduced section is $p_1 = p \omega / \omega_1$. Columns (3) and (4) give values thus calculated. It will be

seen that the real stress increases faster than the nominal stress.

PLATE OF LOWMOOR IRON, No. 142

(Broken with stress in the direction of rolling. Section, 1 sq. in. Elongations measured in 8 ins.)

(1) Stress in tons per sq. in. of initial section p	(2) Elongation in inches e	(3) Area of section ω_1	(4) Stress per sq. in. of reduced section p_1
17	·025	·997	17·05
18	·14	·983	18·31
19	·20	·976	19·47
20	·28	·966	20·69
21	·38	·955	22·00
22	·56	·935	23·54
23	·90	·899	25·59
23·2	1.34	·857	27·08
22·7	[1·65]	[·777]	29·20

The ultimate extension $e = 1{\cdot}65$ consists of an extension 1·34, or 17 per cent., due to the load of 23·2 tons, distributed over the 8-inch length, and a further extension due to local contraction during the period of diminishing load. The rate of extension at the section of fracture is easily seen to be $(\omega - \omega_1)\, l / \omega_1$. This gives for the rate of elongation at the section of fracture 2·29 inches in 8 inches, or 28 per cent., which may be called the elongation at the contraction. How far these deductions are useful in practically determining the quality of the material remains to be determined. Obviously, however, they represent the actual facts of the test more closely than the usual mode of calculation. For comparison a test of Lowmoor plate crossways of the grain is appended:

p	e	ω_1	p_1
16·0	·015	·998	16·03
17	·06	·993	17·13
18	·115	·986	18·26
19	·20	·976	19·47
19·7	[·32]	[·962]	20·48

The area of fracture corresponds to an elongation of 0·316 inch, or 4 per cent., which agrees closely with the measured elongation. This shows there was no local contraction.

The following table gives similar calculations for a steel plate:

MILD STEEL PLATE. Area 1 sq. in.

(Elongations measured in 10 ins.)

p	e	ω_1	p_1
19	·09	·991	19·17
20	·33	·968	20·65
21	·40	·962	21·84
22	·49	·954	23·08
23	·56	·947	24·29
24	·70	·935	25·68
25	·87	·920	27·17
26	1·20	·893	29·12
26·43	2·15	·823	32·11
25·5	[2·55]	[·576]	44·27

The fractured area corresponds to an elongation of 7·3 inches in 10 inches, or 73 per cent. The yield point of this steel was 16·6 tons per sq. in.

203. *Stress at which Local Contraction begins.*—M. Considére[1] has indicated that local contraction must begin when the load on the bar is a maximum. The total load on the actual section is $p_1 \omega_1$, which is increasing so long as maximum load is not reached. Hence, the stress p_1 a given section will carry increases faster than the section diminishes. Consequently if any section contracts more than the rest it thereby becomes capable of carrying a greater load. But when the maximum load is passed this condition, analogous to stable equilibrium, no longer exists. Then $p_1 \omega_1$ is diminishing, and p_1 does not increase so fast as ω_1 diminishes. If any section contracts more than the rest, it becomes less capable than they are of carrying the load, and the deforming action gets concentrated at that part.

204. *General Form of Autographic Diagrams of Different Qualities of Weld and Ingot Iron and Steel.*—Fig. 164 shows a series of autographic diagrams from pieces of Lowmoor plate, 8 inches in length between the clips, at which the extension was taken. Half these are plates broken in the direction of rolling (marked L), and half across the grain (marked X). The yield point is less abruptly marked than in the case of steel. The smaller plasticity of the material across the grain is evident. Many of the plates break at the maximum load.

Fig. 165 shows diagrams from plates of Landore Siemens

[1] *L'Emploi du Fer et de l'Acier*, p. 22.

steel. The extensions are for a 10-inch length. The yield point is well marked, and the plastic elongation beyond the yield point is very large. The material draws out locally so that the load has to be reduced towards the end of the test. Fig. 166 shows diagrams for test bars of a harder steel used in the manufacture of ordnance. The elongations are for a

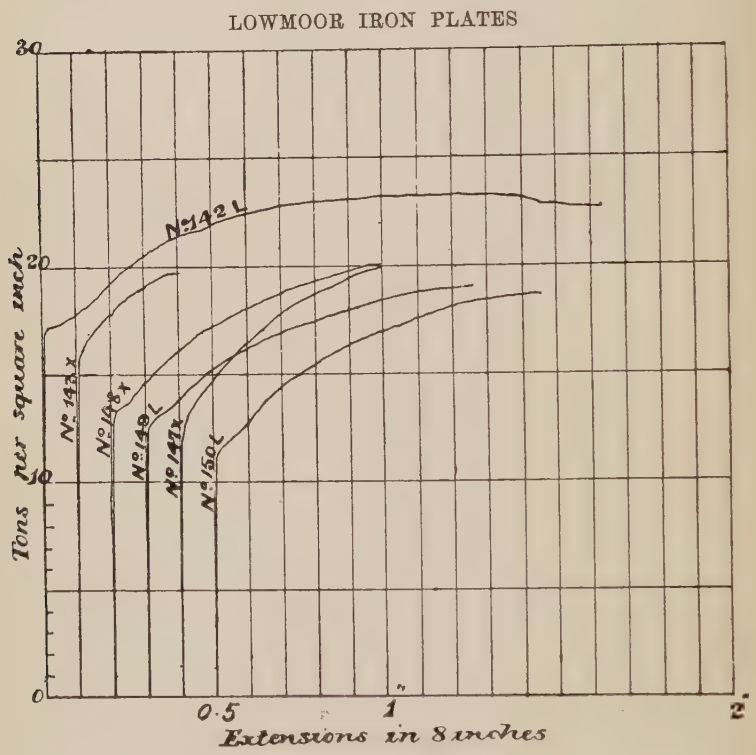


FIG. 164.

gauge-length of two inches. The yield point is distinctly marked. Fig. 167 gives the diagrams of some tests of steel rails. The steel is harder and the yield point is only slightly marked. There is considerable local drawing out indicated by the fall of the load at the end of the test.

205. *Effect of Quick and Slow Rates of Loading on the Strength of Test Bars.*—Before deciding on the details of the tests of the steel for the East River Bridge, experiments were

made to determine whether the strength of the specimens was affected by the rate of loading. Nine test bars of steel, 1 inch square and 24 inches long, were cut from the same rolled bar, and these were used without further preparation.

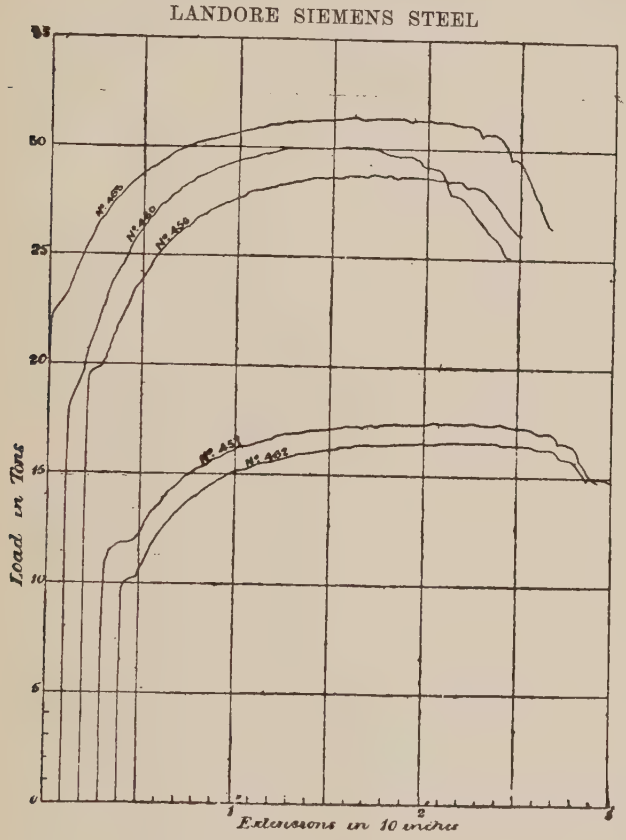


Fig. 165.

Three test bars were broken in periods of 3 minutes, three in periods of 6 minutes, and three in periods of 20 minutes. No difference in ultimate strength was found which could be attributed to the quicker or slower rate of loading.[1] The

[1] Mr. W. Denny appears to have made experiments leading to the same result. See Hackney, 'Forms of Test Pieces,' *Proc. Inst. of Civil Engineers*, vol. lxxvi.

influence of time on the elongation has been discussed in § 74.

206. *Influence of the Form of the Ends of the Test Bar.*— Sir A. B. W. Kennedy made some experiments on the effect of varying the form of the ends of plate test bars on the strength and elongation.[1] The forms tried are shown in

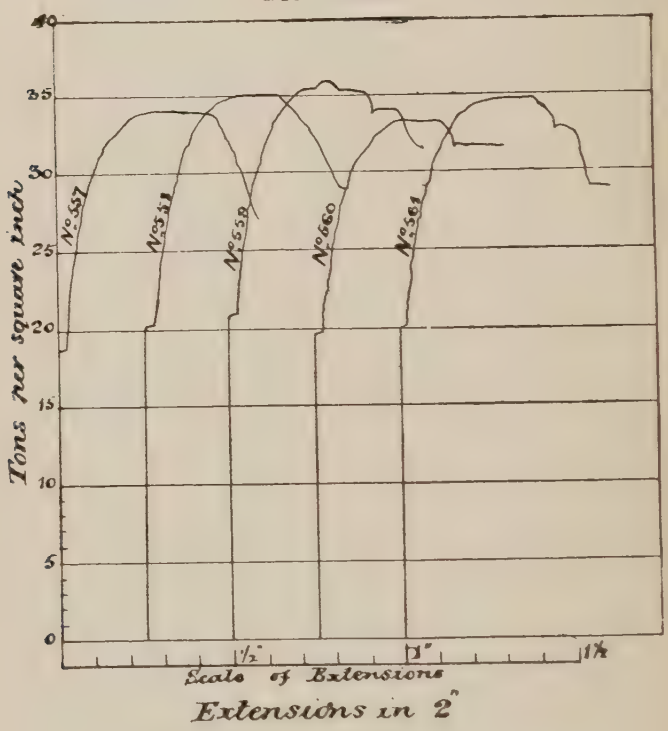


FIG. 166.

fig. 168. With soft basic steel, annealed, there was no difference of strength or extensibility distinctly traceable to the form of the ends of the test bar. Even form II. broke fairly in the middle, and not at the shoulder. Some pieces of common wrought-iron plate, however, showed marked differences when tested in the forms II. and VII. Hard or inferior material seems, therefore, to be affected by the form of the ends.

[1] *Proc. Inst. of Civil Engineers*, vol. lxxvi.

207. *Influence of the Skin on the Strength and Elongation of Wrought-iron Bars. Rough and Turned Bars.*—The results of tests on wrought iron are more irregular than those on

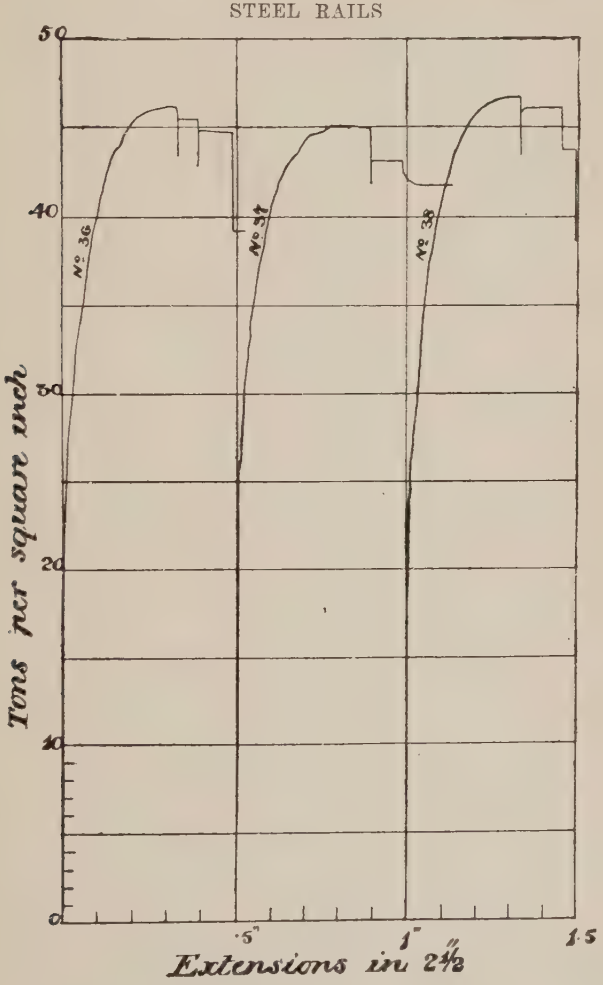


FIG. 167.

steel. In the case of round bars there is also some difference, according as the bar is tested rough or turned. The following table gives average results of tests of 72 bars of ¾, 1⅛, and 1½ ins. diameter, half of which were rough and half turned.

TABLE VI. RESULTS OF TESTS OF TWO STRIPS OF BASIC STEEL, UNANNEALED, AND FOUR STRIPS OF WROUGHT-IRON PLATE—ALL SIMILAR EXCEPT IN FORM OR ENDS (KENNEDY)

(Plates about $\frac{5}{8}$ in. thick and $1\frac{1}{2}$ in. wide)

Form	Limits of elasticity in tons per sq. in.	Breaking stress in tons per sq. in.	Extension per cent. in a length (always including fracture) of					Contraction of area, per cent.	—
			10 ins.	8 ins.	6 ins.	4 ins.	2 ins.		
Basic steel, II. .	18·87	28·18	21·8	23·9	27·6	31·7	44·5	51·3	Square corners
„ VII. .	17·46	29·12	20·8	22·5	25·8	31·5	44·5	51·0	Hollow corners
Means . .	18·16	28·65	21·3	23·2	26·7	31·6	44·5	51·2	
Wrought iron, II. .	15·95	21·40	4·6	4·8	4·7	4·5	5·0	9·3	Square corners
„ „ II. .	15·55	23·60	6·4	6·7	6·7	7·2	8·5	11·0	„ „
Means . .	15·75	22·5	5·5	5·7	5·7	5·8	6·7	10·2	
Wrought iron, VII.	16·05	24·58	14·0	14·2	15·5	17·2	23·0	21·2	Hollow corners
„ „ VII.	17·81	25·28	14·0	14·5	15·7	18·0	21·0	18·9	„ „
Means . .	16·93	24·93	14·0	14·4	15·6	17·6	22·0	20·1	

Description of iron	Tensile strength, tons per sq. in.		Elongation per cent.			
	Rough	Turned	Rough		Turned	
	—	—	In 4 diams.	In 8 diams.	In 4 diams.	In 8 diams.
Smithing Iron . . .	23·54	23·58	31·8	27·3	29·4	24·4
Rolling Stock Iron . .	23·30	23·50	36·4	29·9	34·0	27·8
Best Yorkshire . . .	22·30	22·30	40·9	34·4	37·5	30·3
Means .			36·4	30·5	33·6	27·5

The ratio of the elongations in 4 and 8 diameters is on the average 12 to 10. The ratio of the elongation of the rough

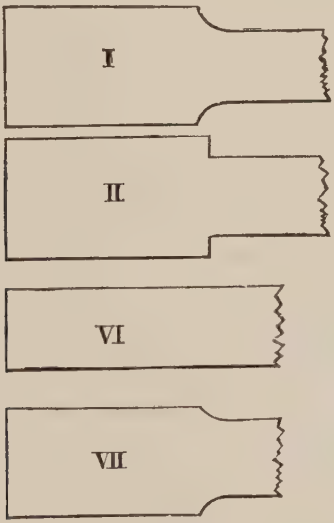


Fig. 168.

bars to that of the turned bars is about 10 to 7. The strength of rough and turned bars is practically the same.

208. *Relative Extensions in Steel Bars with Gauge-lengths of* 4 *and* 8 *Diameters.*—A series of tests of mild steel with different gauge-lengths gave the following results. The extensions are calculated for fracture at the centre of the gauge-length. The tenacity of the bars varied from 28·9 to 30·6 tons per sq. in.

ELONGATIONS PER CENT. IN GAUGE-LENGTHS OF FOUR AND EIGHT DIAMETERS

Bar	Tenacity tons per sq. in.	Approximate diameter of bar ins.	Elongations per cent.		Ratio $\frac{e_4}{e_8}$
			In 4 diams. e_4	In 8 diams. e_8	
A. long . .	30·6	1	37·20	27·95	1·33
A. short . .	30·4	1	35·34	27·37	1·29
B. long . .	29·9	1¼	32·34	26·17	1·23
B. short . .	27·4	1¼	32·22	26·16	1·23
C. long . .	29·0	1¾	29·27	23·21	1·27
C. short . .	28·9	1¾	31·95	26·48	1·21

On the average the elongation per cent. in 4 inches is one and a quarter times that in 8 inches.

209. *Tests of Mild Steel in the Directions of Rolling and Across it.*—The strength and ductility of wrought iron are materially different in the direction of rolling and at right angles to it, but it is commonly assumed that in mild steel there is no measurable difference. This is not strictly true of the ductility. Prof. Krohn and F. Knitzle [1] found the following averages from tests of a large number of bars and plates, &c. The results under (*a*) are for plates rolled in universal rolling mills ; (*b*) for ordinary plate mills ; and (*c*) for girder sections :

—	*a*	*b*	*c*
Tensile strength, tons. per sq. in. :			
In direction of rolling . . .	25·3	25·2	25·7
Transverse to direction of rolling .	26·0	25·4	25·3
Elongation per cent. :			
In direction of rolling . . .	27·5	25·5	27·4
Transverse to direction of rolling .	22·8	24·3	24·3

Variation of Quality in Pieces cut from the same Plate.—Some experiments show a more or less considerable difference of quality in pieces cut from the same plate. In some of these cases the differences are due to errors in testing. If the testing-machine is not itself inaccurate, imperfect centring of the specimen in the machine, or imperfect gripping of the specimen in the shackles, may give rise to considerable apparent differences of strength. But in other cases there appear to be real differences in the quality of the material, and the limits of such differences are not at present determined.

[1] *Proc. Inst. Civil Engineers*, vol. cxii. p. 451.

Sir B. Baker has stated that entire bars, 16 feet long, 10 inches wide, and 1 inch thick, gave an average tenacity of 19 tons per sq. in.; while ordinary test pieces, cut from the same bars, broke at a stress 35 per cent., and even in some cases 75 per cent., higher.[1] An iron plate was cut up in the workshop of the Compagnie des Chemins-de-fer de P. L. M. into 32 test pieces.[2] The strength lengthways varied from 20·32 to 29·21 tons per sq. in., and crossways from 20·32 to 23·50. The stretch varied from 12·5 to 21·5 per cent. lengthways, and from 7·0 to 14·5 per cent. crossways.

210. *Influence of the Amount of Reduction in Rolling on the Strength of Iron Bars.*—In the report of the United States Testing Board for 1881, data are given showing the amount of work put on a bar considerably affects its tenacity and yield point. Tests of iron for chain cables showed differences of strength for different diameters, and this led to a special series of experiments, in which bars of the same iron were rolled so that the section of the finished bar had greatly different ratios to the area of the pile from which it was rolled. These bars were very uniformly heated, as it was found that underheating in rolling tended to give an increased tenacity and higher yield point, and overheating a reduced tenacity and lower yield point.

INFLUENCE ON THE TENACITY AND ELASTIC LIMIT OF THE AMOUNT OF REDUCTION IN THE ROLLS

IRON BARS

Size of bar	Area of bar in per cent. of area of pile	Tensile strength, tons per sq. in.		Yield point, tons per sq. in.		$\frac{f_y}{f_t}$
		Rough bar	Core, or bar turned down f_t	Rough bar	Turned bar f_y	
4	15·7	—	20·6	—	10·45	·51
3½	12·0	—	21·0	—	11·1	·53
3	8·8	—	21·3	—	11·8	·55
2½	6·1	21·1	21·1	13·25	13·3	·63
2	4·4	21·4	21·6	16·0	14·2	·66
1¾	6·7	22·5	21·8	16·1	17·4	·80
1½	4·9	22·7	23·1	15·6	16·3	·71
1¼	3·4	23·5	22·2	17·6	18·1	·82
1⅛	4·0	22·3	22·5	15·8	16·8	·75
1	3·1	23·1	22·8	17·4	17·2	·75
⅞	4·9	22·6	22·5	15·1	14·8	·67
¾	3·6	22·6	22·4	15·1	16·0	·72
½	2·2	23·3	23·5	17·1	17·4	·74
⅜	3·7	24·1	24·1	17·2	17·9	·74

The increase of f_y/f_t in the first half of these results is noteworthy.

[1] *Proc. Inst. Civil Engineers*, vol. lxxvi. p. 95. [2] Lebasteur, *Les Méaux*, p. 194.

It is no doubt due to an analogous difference in the amount of work done on the material in hammering and rolling that large forgings are found to be weaker than small bars, and the interior of large forgings weaker than the exterior. Thus, for instance, a propeller shaft of the U.S. despatch-boat *Dolphin* broke on the trial trip, and test bars cut from the shaft gave the following results:

—	Yield point, tons per sq. in.	Tenacity, tons per sq. in.	Elongation per cent.
From centre of shaft . .	15·2	24·1	2
From surface of shaft . .	14·3	35·7	18

Some tests of wrought iron, cut in different directions from forgings of large size, are given by Mr. Mallet in a paper on the 'Coefficients of Elasticity and Rupture in Massive Forgings.'[1] The weakest wrought iron was cut radially from the end of a heavy cylindrical forging, which had been exposed during forging to heating for about six weeks. Its elastic limit in tension was only $3\frac{1}{4}$ tons, and it broke at $6\frac{1}{2}$ tons per sq. in. Mr. Mallet concluded that the iron of very heavy shafts, forged guns, or cranks may be expected to have an elastic limit of 7 tons per sq. in., and to break at a tension of 15 tons per sq. in. The following are a few of Mr. Mallet's results:

Material	Tension in tons per sq. in.	
	At elastic limit	At fracture
Hammered slab (12″ × 4″) . .	15·3	24·1
Rolled slab (12″ × 4″) . . .	10·9	23·0
Forged slab (48″ × 48″ × 12″) . .	8·75	18·6
Mersey gun:		
Original faggot bars . . .	12·0	21·9
Longitudinal cuts	9·8–10·9	19·7–17·9
Circumferential cuts . . .	6·6–5·5	16·4–16·7
Transverse cut	3·28	6·56
Borings from gun, reforged and rolled into a bar	5·47	22·32

[1] *Proc. Inst. of Civil Engineers*, vol. xviii., Session 1858–9. This paper is interesting from containing probably the earliest carefully plotted stress-strain diagrams for tension and pressure.

211. *Hammer Hardening and Cold Rolling.*—It is well known that ductile materials can be rendered more elastic and harder by hammering, planishing, or wire-drawing cold, and this action is identical with that which occurs in mechanical operations in many ways, sometimes with useful, sometimes with prejudical, results. Whenever a ductile material is subjected to deformation by pressure at temperatures below those at which the metal is plastic, the strength and elastic limit are raised, but the elongation at fracture is diminished. The elasticity is increased, but the plasticity is diminished. The author has noticed that, in very long rail bars, the colder end which passes last through the rolls has a higher yielding point and strength, but less elongation at fracture, than the hotter end. The following are some results from pieces cut from steel rails rolled 150 feet long:

Test No.	—	Tenacity in tons per sq. in.	Extension in 2½ inches, per cent.	Contraction of area, per cent.	Work done per cub. in. in inch-tons up to max. stress
36	Hot end	46·37	22·0	49·17	5·15
37	„	45·03	26·0	54·63	6·72
38	„	46·73	22·0	46·85	5·45
40	Cold end	49·84	17·6	33·17	7·07

The work done was measured from an autographic diagram.

Many years ago an American process of cold rolling was introduced. Round bars passed through rolls cold were straightened, polished, and rendered stronger and stiffer. The following experiments by Sir W. Fairbairn on a bar of good Dudley iron show how the mechanical properties of the material were affected by the process:

Material	Tensile strength, tons per sq. in.	Elongation in 10 ins., per cent.
Rough rolled bar, 1¼ inch diameter, in ordinary state	26·0	20·3
The same, turned down to 1 inch diameter in lathe	26·7	22·4
Bar, cold, rolled to 1 inch in diameter	38·4	8·0

The strength increased one-third, and the plastic elongation diminished more than one-half.

The following results are given by M. Considére:[1]

[1] *L'Emploi du Fer et de l'Acier*, p. 148.

Material	Elastic limit in tons per sq. in.	Tenacity in tons per sq. in.	Elongation, per cent.
Very mild steel in ordinary state	16·07	26·99	26·5
The same, compressed by hydraulic press at 32 tons per sq. in.	22·67	28·32	17·0
Ship steel in natural state	18·80	33·34	18·0
The same, reduced by cold rolling from 10 to 9·45 mm. thick	26·92	34·61	11·5
Iron plate, natural state	14·48	23·75	15·0
The same, reduced by cold rolling from 8 to 7·1 mm. thick	26·42	29·78	7·0

The gain of ultimate strength is here not large, but the rise of the elastic limit (probably the yield point) is very marked. The diminution of plasticity, shown by the ultimate elongation, is also marked. Wire-drawing is a process similar to cold rolling, and in wire-drawing the increase of strength is very considerable.

The effect produced by hammer hardening or cold rolling is entirely removed by annealing; and doubtless it is to the removal of some effect of this kind, due to rolling at too low a temperature, that the diminution of strength by annealing, which sometimes occurs, is due.

212. *Local Hardening.*—If a plate is sheared or punched a very considerable lateral pressure is exerted on the metal near the cut edge. The action diminishes rapidly from the cut edge towards the interior of the mass, like the stress in a thick cylinder subjected to internal pressure. For about $\frac{1}{8}$ inch from the cut edge the metal is hardened, and its power of extension greatly diminished. M. Barba cut from a punched plate the ring of metal surrounding a punched hole, and found it to be extremely brittle and incapable of bending. M. Considére has shown that a permanent condition of compressive stress is induced in the ring immediately round the hole.

M. Barba showed that rimering out a ring $\frac{1}{8}$-inch thick round the punched hole, or annealing the plate, entirely removed the prejudicial effect of punching. The punching is more injurious the thicker the plate, and this is obviously due to the increase of lateral pressure in punching thick plates. It is less injurious if the die-block hole is larger than the punch, for that diminishes the lateral pressure. Sheared strips of ductile material are brittle when bent.

Some experiments of M. Barba showed that the diminution

of strength in a bar in which a hole had been punched (reckoned on the net section) was greater the wider the bar.

Thus, some steel test bars 0·28 inch thick were punched with a hole 0·68 inch in diameter. The normal tenacity of the steel was 32·7 tons per sq. in. The punched bars of different widths gave the following results:

Width of bars in inches . .	1·28	2·0	2·72	3·44	4·16	4·88
Tenacity—cylindrical holes .	27·1	25·9	25·3	22·7	24·3	23·1
„ conical holes . .	31·7	28·3	26·3	22·4	22·9	23·7

Further experiments have been made by M. Considére on a plate of Siemens-Martin steel, containing 0·34 per cent. of manganese and 0·22 per cent. of carbon, and a plate of Bessemer steel, containing 0·38 per cent. of manganese and 0·33 per cent. of carbon. The normal tenacity of these plates was 32·7 and 38·1 tons per sq. in. M. Considére first verified M. Barba's result, and determined that the increase of strength in the narrow plates was not due to the lateral expansion of the narrow bar under the action of the punch. He then tried bars with a punched semi-hole on each side, leaving a strip of metal between them. The following were the results:

Material	Normal tenacity	Tenacity of bar when distance between the holes was in inches				
		·2	·24	·32	·56	1·2	2·0
Martin steel . .	32·7	42·6	41·5	40·6	33·3	28·6	27·2
Bessemer steel . .	38·1	—	—	46·8	39·6	33·6	30·6

When the distance between the holes is less than $\frac{1}{2}$ inch, the punched bar is stronger than the unpunched bar. For wider bars the reverse is the case. Part of the excess of strength in the narrow bars is no doubt due to the suppression of drawing-out, explained in § 68. By tests on plates with drilled holes, M. Considére found that 5 tons increase of strength in the 0·2-inch bar was due to this cause. There remains another 5 tons increase, due directly to the punching. In this very narrow bar the whole of the metal between the holes was hardened by the action of punching, and the increase of strength is that due to cold working. As the bar is made wider it comes to consist of hard metal near the holes, and

softer metal, unaffected by punching, between. This involves unequal distribution of stress. The bar tears at the rigid material, and the tear doubly weakens the bar, partly by loss of section, partly by the unsymmetry which results.

Suppose fig. 169 represents at o *f* the normal stress-strain diagram of the material, and at o *e* the stress-strain diagram for the material hardened by punching. If the bar stretches an amount o *a*, the stress near the hole will be *a d*, and that of the uninjured material *a c*. The bar *must* tear at the edge of the hole when the strain reaches the value o *b*.

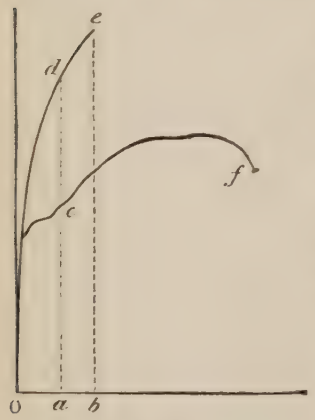


Fig. 169.

The application of these considerations is wider and more important than the question of the deterioration of plates by punching. It has been seen that in many ways the plasticity of the material may be altered, so that the yield point disappears and the extensibility is diminished—by rolling at too low a temperature, by sudden cooling, by bending, hammering, cold rolling, or by shearing or punching. So long as such an action is general, the only effect is that a more rigid material is made out of a ductile one. But if, as must often happen, the action is local, then the effect on the strength, like that of the thin ring of hard metal round a punched hole, is more serious. To know the danger, however, is sufficient. Either local hardening can be avoided, or, if unvoidably produced, it can be destroyed by annealing.

III. Influence of Differences of Thermal Treatment

213. *Hardening, Tempering, and Annealing.*—If steel containing carbon, manganese, or phosphorus in sufficient quantity is heated to about 1,450° or higher[1], and then suddenly cooled by plunging into a bath of cold liquid, it becomes harder, stronger, and less plastic. The more of the hardening elements in the steel (up to a certain limit), and

[1] With 0·4 per cent. of carbon, steel hardens, if heated to 1,560° F.; with 0·9 per cent. if heated to 1,470°; with 1·40 if heated to 1,380°.

the lower the temperature, and the greater the power of absorbing heat in the cooling liquid employed, the greater the hardness produced. Water hardens steel more actively than oil, and pure water has a greater effect than soapy water.

In plunging the heated steel into a cooling liquid the exterior loses heat first, and contracts on the interior. There

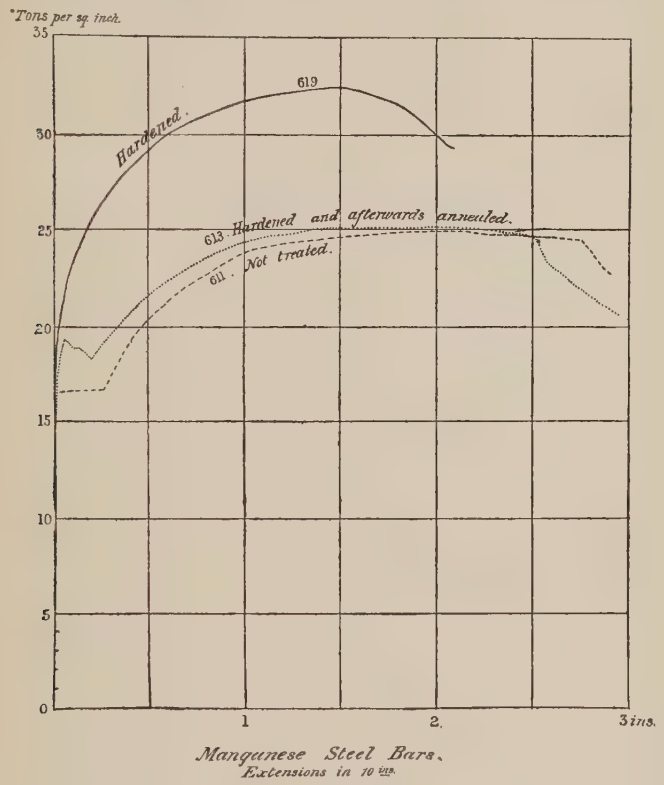


Fig. 170.

thus result tensions in the exterior, which may exceed the elastic limit and cause permanent stretching or even fracture. Afterwards, the interior cools and contracts. But it is now attached to the stretched exterior, and in turn is put into tension. Thus there may arise in hardening a condition of great internal stress. The cracking and twisting which often occur in hardening are indications of this condition of stress. M. Caron has observed that the volume increases in

hardening. M. Considére states that if a hardened bar is cut in two by a parting tool in the direction of its length the pieces become curved, with the concavity on the planed side.[1]

By reheating hardened steel and allowing it to cool slowly, the hardening previously induced is diminished. This is termed tempering, or letting down the temper. If the steel is raised to 1,300° or higher, the whole of the induced hardening disappears, and the process is then termed annealing. In annealing the temperature must be high enough, but should not approach the fusing-point, or other changes occur. The cooling must be slower the larger the mass to be annealed, and in the case of large masses requires days or even weeks.

Alternate hardening and annealing alter the steel, somewhat in the same way as mechanical forging.[2] The steel, originally coarsely crystalline, and with small elongation, changes to a condition of finer grain and greater toughness. The hardening is most safely effected with oil.

The autographic diagrams (fig. 170) show clearly the changes in the condition of the material due to hardening and annealing. They are diagrams from three similar bars of mild steel, one of which was tested without preparation, the second hardened in water, and the third hardened and subsequently annealed. The yield point disappears in the hardened bar, the strength is increased, and the plastic elongation diminished. Annealing restores the steel very nearly to its original condition, the annealed bar, however, having a raised yield point and slightly increased elongation.

Manganese steel	Original state	Hardened	Hardened and annealed
Tenacity in tons per sq. in. . . .	24·71	32·69	25·17
Elongations in 10 inches, per cent. .	29·8	20·1	30·3
Stress at yield point	16·73	—	18·76
Contraction of area, per cent. . .	51·6	55·3	62·3

Mr. Milton has given the following results of tensile tests of plates, some of which were tested in their ordinary state, the others after heating to red heat and quenching in water at 80°:

[1] *L'Emploi du Fer et de l'Acier*, p. 10.

[2] Colonel Maitland, R.A., 'On the Treatment of Gun Steel,' *Proc. Inst. Civil Engineers*, 1887.

Material	Original state		After heating and quenching	
	Tenacity in tons per sq. in.	Elongation in 10 ins., per cent.	Tenacity in tons per sq. in.	Elongation in 10 ins., per cent.
Very mild steel . . .	25	24	38	10
Harder mild steel . .	29	23	43	5
„ steel . . .	35	22[1]	50	0
„ „ . . .	35	22	43[2]	11

The following results are given by Lebasteur on steel from Terre Noire, showing the increased effect of tempering as the carbon increases: [3]

(The bars were 0·8 in. diameter and 7·9 in. between gauge-points. Stress in tons per sq. in.)

Carbon, per cent.	Original state			Hardened in oil			Hardened in water		
	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.
0·150	11·57	23·11	32·5	20·83	29·72	28·6	19·56	28·83	19·0
0·490	14·61	30·48	24·8	28·32	44·77	12·0	30·48	49·53	2·5
0·709	19·56	43·31	10·0	43·69	68·00	4·0	} Broke in tempering		
0·875	20·83	44·39	8·4	57·47	67·31	1·0			
1·050	25·08	54·61	5·2	Broke in tempering					

A corresponding series of tests of steels containing different proportions of manganese was also made, the other constituents of the steel being kept constant.

Manganese per cent.	Original state			Hardened in oil			Hardened in water		
	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.
0·521	16·70	32·90	24·5	26·48	48·58	12·0	—	—	—
0·060	19·81	38·80	21·4	41·28	62·87	—	—	—	—
1·305	26·16	48·58	17·4	} Cracked in tempering			—	—	—
2·008	30·29	56·20	10·5				—	—	—

A similar series of tests was made with steel containing 0·247 to 0·398 per cent. of phosphorus. The influence of phosphorus is like that of carbon, but less energetic.

[1] In 7 inches, and after annealing. [2] Quenched in soapy water.
[3] Lebasteur, *Les Métaux*, p. 72.

214. *Oil Tempering.* — Steel forgings are now often tempered in oil. The steel is heated to from 1,300° to 1,550° F. and suddenly cooled in oil. The forging is then usually annealed by heating to 900° F. and slow cooling. The strength, especially the elastic strength, is considerably raised by this treatment, and the ductility is not greatly diminished. The following are some results:

OIL-TEMPERED STEEL

—	Strength at yield point, tons per sq. in. f_y	Tensile strength, tons per sq. in. f_t	Ultimate elongation in 2 in., per cent. 100 λ	$\frac{f_y}{f_t}$
Untempered .	13	31	28	0·55
Tempered in oil .	29	43	21	0·72

Mr. H. F. I. Porter, in a paper on 'Steel Forgings for Pumping Engines,'[1] has given the following results as now obtainable in large steel forgings. The test bars were cut from full-sized prolongations of the forgings, and were 0·5 inch diameter.

—	Elastic strength, tons per sq. in. f_y	Breaking tensile strength, tons per sq. in. f_t	Extension in 2 ins. per cent. 100 λ	$\frac{f_y}{f_t}$
Mild steel, annealed . .	12·5	26·0	28	·48
Med. hard steel, annealed .	16·5	35·6	23	·46
„ „ oil tempered	20·0	35·6	25	·56
Nickel steel, annealed .	20·0	35·6	23	·56
„ No. 1, oil-tempered	22·3	35·6	25	·63
„ No. 2. „ .	26·8	40·0	22	·67

For oil-tempering the forging had an axial hole.

215. *Welding.*—It is one of the most valuable of the properties of iron and steel that two pieces raised to a sufficient temperature and pressed together unite by welding. The welding temperature varies with the percentage of carbon in the steel. With less than 0·9 per cent. of carbon the steel can be welded with sand as a flux. With 0·9 to 1·1 per cent. of carbon it can be welded if borax is used as a flux. With more carbon it can only be welded with difficulty or not at all.

Bauschinger found that soft steel or ingot iron bars of

[1] *Proc. Am. Waterworks Association*, 1897.

EXPERIMENTS ON THE TENSILE STRENGTH OF STEEL AT THE TERRE NOIRE WORKS.[1] NORMAL AND OIL-TEMPERED

(Diameter of bars, 0·55 in.)

Material	Percentage of carbon	Stress in tons per sq. in.		Elongation in 4 ins., per cent.
		Elastic limit	At breaking	
Forged steel (containing about ¼ per cent. of manganese and a trace of silicon)	·15	13·70	22·24	34·0
	·49	16·32	30·40	24·0
	·709	19·69	42·36	15·0
	·875	21·31	46·16	9·5
The same after hardening in oil	·15	20·43	28·16	28·6
	·49	27·79	43·92	12·0
	·709	42·86	66·72	4·0
	·875	56·38	66·14	1·0
Cast steel, not forged (containing about ¾ per cent. of manganese and ¼ per cent. of silicon)	·287	13·08	27·85	8·8
	·459	16·51	26·98	3.0
	·750	19·00	40·00	3·5
	·875	24·42	40·18	1·5
The same, after hardening in oil and annealing	·287	19·69	32·27	24·6
	·459	20·87	34·58	19·2
	·750	22·30	46·23	14·3
	·875	28·66	51·46	3·5

0·15 to nearly 2 sq. ins. in section had at the weld a strength varying from 57 to 105 per cent. of the strength of an unwelded bar. The mean strength at a weld was 89 per cent. of the strength of the bar. With wrought-iron bars the strength varied at the weld from 83 to 102 per cent. of the strength of the unwelded bar, the mean ratio being 95 per cent. Welds made with the steam hammer were 10 per cent. stronger for mild steel and 5 per cent. stronger for wrought iron on the average than welds made by hand.

The author made some tests of small electrically welded bars of two qualities, with the following results:

Percentage of carbon	Ratio of strength at weld to strength of bar, per cent.	
	Series A	Series B
·75	52	68
1·00	76	51
1·00	50	84
1·15	89	113
1·15	75	117
1·25	75	86

[1] *Proc. Inst. Mech. Eng.*, 1880, p. 182.

216. *Injurious Effect when Steel is worked at a 'Blue' Heat or Colour Heat.*—It has long been known, in a more or less vague way, that in cooling from a welding heat steel passed through a condition in which it became brittle and dangerous to work. *First*, it should be noted that there is a temperature at which the steel is brittle and little capable of being bent. In 1881 the Board of Trade, in a Memorandum on Steel, published the result of experiments made at the works of the Steel Company of Scotland. Forty-eight plates were taken, and strips cut from each. Half the strips were bent cold to an angle of 180° round a bar of a diameter equal to twice their thickness. The whole of the strips stood the test. Corresponding strips were heated in boiling tallow and bent at that temperature. Every one of the strips cracked before the bending reached 180°. *Second*, a plate heated and allowed to cool is no worse for the operation; but this very curious action appears to occur. If, while in cooling the steel is at blue heat or colour heat, mechanical work by hammering or bending is done on the then brittle plate, it will be found when cold to be seriously injured in quality.

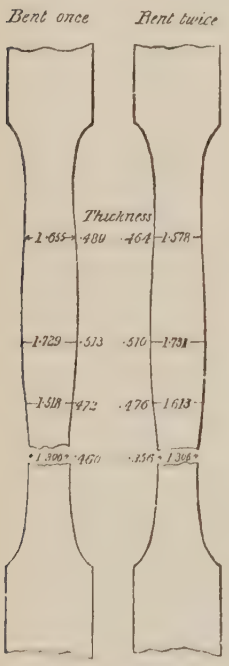


Fig. 171.

Prominent attention was first directed to the injurious effect of working steel at a blue heat in a paper by Mr. Strohmeyer.[1] The most interesting results were obtained by the bending test. The test strips were bent alternately in opposite directions till they broke, and the number of bendings was taken to be an index of the ductility of the material. The test strip was clamped between a steam-hammer and its anvil, and the projecting end was bent down by hammering (over a mould with rounded angle) through an angle of 45°. The test strip was then turned over and bent in the opposite direction. Mr. Strohmeyer takes 'blue heat' as a convenient expression for any temperature between 470°

[1] *Proc. Inst. Civil Engineers*, 1886.

and 600°C. It was found that while a test strip bent cold would stand twenty to twenty-six bendings before cracking, if it was once bent while at blue heat and allowed to cool, it broke afterwards with very few bendings. The table gives a summary of the results.

The first two lines show that both steel and wrought iron suffer much fewer bendings at blue heat than cold. Next, if a strip is bent once at blue heat and allowed to cool, it is afterwards a quite different material, much more brittle, and capable of suffering very little bending. The last series of results show that simple cold bending reduces the ductility much more slowly, though iron reaches its limit of endurance sooner than steel.

Conditions to which the strip had been brought	Average No. of bendings before cracking			
	Medium hard Steel, $\frac{5}{8}$ in.	Mild steel, $\frac{5}{8}$ in.	Very mild steel, $\frac{5}{8}$ in.	Lowmoor iron, $\frac{3}{16}$ in.
Unprepared or annealed .	21	$12\frac{1}{2}$	26	20
Bendings while at blue heat	$2\frac{1}{2}$	$1\frac{1}{2}$	$2\frac{1}{2}$	3
Bent at blue heat once and cooled	3	$2\frac{1}{3}$	11	12
Bent at blue heat twice and cooled	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	10
Bent once cold . . .	20	$9\frac{1}{2}$	—	
„ twice „ . . .	$19\frac{1}{2}$	$8\frac{1}{2}$	19	13
„ four times cold . .	—	—	13	11
„ eight „ . .	—	—	15	2

The following experiments were suggested to the author by Mr. Strohmeyer's paper. A plate of mild 27-ton steel was broken in the testing-machine in the ordinary way. The longer piece after this test was heated to a temperature a little below redness, and while at that temperature it was bent to a shallow curve and straightened again. It was then tested in the ordinary way. The results were these:

	First test	Second test, after bending while hot
Tenacity . . .	27	32 tons per sq. in.
Contraction . .	51	21 per cent.

These results seem to show that the tenacity is increased at the expense of the ductility. Some test pieces of the same mild steel were heated to red heat, placed on a V-block, and quietly bent to an angle of about 15° at each end out of straight. The bending pressure was put on just as the redness disappeared. The test pieces were then straightened in the same way. Lastly, they were tested by tension. Fig. 171 shows the result obtained. In the place which was the middle of the curvature in bending there is scarcely any measurable contraction of area, or extension. On one side of the middle of the bar, where there was hardly any bending, the material is still ductile, and draws down. The figure shows the widths and thicknesses of the bars. The elongations in each inch length were as follows:

Elongations in each Inch.

Bar bent once and straightened.		Bar bent and straightened twice.	
0·048		0·120	
0·152		0·154	
0·138		0·156	
0·080		0·064	
0·020	Heated part.	0·000	Heated part.
0·010		0·002	
0·138		0·082	
0·287		0·174	
0·622	Break.	0·610	Break.
0·160		0·232	
0·100			

In the part heated and worked (by bending) the steel is not weaker, but it is stiffer. The bar has been rendered unhomogeneous, and consists of portions of quite different extensibility. It is easy to see that by locally treating a plate in this way it may be rendered extremely treacherous, even without assuming that the heating and bending has created a condition of internal stress.

The results in the following table, obtained by Mr. Webb, at Crewe, carry the same lesson of the gain of strength with the loss of ductility. For convenience of comparison the results for plates bent or hammered at blue heat, and not annealed after, are separated from the others. All were tested cold, except those marked as tested hot:

Condition of material	No. of tests	Tenacity in tons per sq. in.	Elongation in 10 ins., p.c.
Ordinary plate, annealed	3	30·96	23·6
Hammered while blue hot and annealed	2	30·26	23·8
Bent while blue hot and annealed	3	30·74	22·1
Bent red hot and cooled	3	31·65	22·5
Annealed plates bent cold	3	32·42	12·5
„ „ and annealed	3	30·60	23·63
Bent three times blue hot	1	38·04	4·3
Hammered while blue hot	2	35·24	10·05
Bent once blue hot	3	31·95	7·5
Tested while blue hot	2	38·80	11·4

IV. Strength and Ductility at Different Temperatures

217. As early as 1856 Sir W. Fairbairn[1] made tests of the strength of wrought-iron plate and rivet iron at different temperatures. With plate iron there was no great decrease of strength till dull red was approached, and then the tenacity rapidly diminished. With rivet iron the strength was slightly greater at — 30° F. than at 60° F. With rise of temperature the strength increased from 28 tons per sq. in. at 60° to 38·4 tons at 435°. At red heat the strength fell to 16 tons. Knut Styffe made similar experiments in a more perfect way. He found the strength and extensibility of iron and steel was not diminished by cold. At temperatures between 212° and 392° the strength of steel is the same as at ordinary temperature, but the strength of iron is greater than at ordinary temperature.

M. Pahkoff[2] made experiments on soft iron and steel plates at temperatures of 63° and —2° F. There was an increase of strength and of elongation at the lower temperature. According to Barba, steel has at 400° F. an increase of strength of 30 per cent., and a decrease of elongation of 30 per cent. The maximum strength is reached at 572°, and for higher temperatures decreases rapidly.

Amongst the most careful of the experiments on the effect of temperature are those by Kollmann, at Oberhausen. Three materials were used, the quality of which may be judged

[1] *Report of the Brit. Assoc.*, 1857, p. 405.
[2] *Proc. Inst. of Civil Engineers*, vol. lxxxiii. p. 513.

from the following summary of the properties when tested at ordinary temperature:

Material	Tenacity in tons per sq. in.	Stress at elastic limit in tons per sq. in.	Elongation, per cent.
Fibrous iron . . .	23·5	17·1	17·5
Fine-grained iron . .	25·4	17·4	20·0
Bessemer steel . .	37·8	24·5	14·5

These experiments show a regular decrease of strength with increase of temperature in all cases. The following table, calculated by Roelker,[1] gives the strength at different

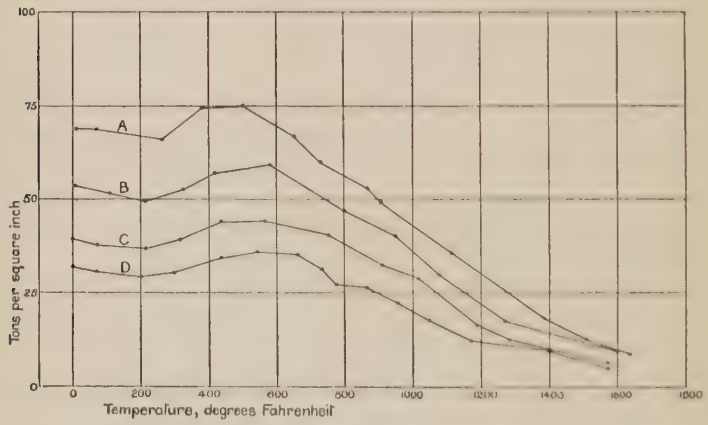


FIG. 172.

temperatures in terms of the strength at ordinary temperatures. For comparison the results of some experiments made by the Franklin Institute are added:

Temperature. F.	Fibrous wrought iron	Fine-grained iron	Bessemer steel	Wrought iron, Franklin Institute
0°	100	100	100	96
100	100	100	100	102
300	97	100	100	106
500	92·5	98·5	98·5	104·5
700	81·5	90	68	92
1,000	26	36	31	36
1,500	10	15·5	12	—
2,000	3·5	5	5	—

[1] *Proc. Inst. Civil Engineers*, vol. lxvii. p. 437.

Mr. Barnaby made experiments on iron and steel for the Admiralty, and these experiments are important, both as being recent and made on test bars of reasonably large size. The bars were partly heated in oil, partly in sand; generally, however, they were taken out of the hot bath and broken as quickly as possible. The temperature was judged from the colour of the fractured surface, or in some cases by observing whether tin or lead melted when placed in contact with the bars.

Experiments on the Influence of Temperature on the Strength and Elongation of Iron and Steel. By Mr. Barnaby

(Elongations in 8 inches)

—	Temperature. F.	Tenacity, tons per sq. in.	Elongation, per cent.
BB Boiler iron lengthways	60°	23·93	23·95
	450	27·08	8·38
	490	27·4	12·5
	60	22·39	13·28
	500	27·15	10·93
	530	26·3	10·15
The same across fibre	60	21·75	9·3
	450	24·6	6·24
	490	22·6	3·12
Bowling iron	60	21·1	15·62
	490	24·4	12·5
	500	23·2	9·37
	550	27·6	17·18
	850 to 900	19·3	18·75
	60	24·8	23·43
	420	30·3	21·87
Bessemer plate	60°	26·07	27·34
	450	40·5	14·06
	520	38·7	17·18
	880	24·02	26·56
Siemens-Martin plate	60	29·10	25·78
	430	33·45	14·06
	490	34·5	18·75
	610	28·0	18·7
	630	30·83	18·74
Bessemer plate	60	28·49	21·87
	430	38·4	18·75
	550	33·08	17·18
	580	18·56	25·0

Tests of Steel at Different Temperatures at Watertown Arsenal.—Some very complete tests of the effect of temperature on steel with different percentages of carbon were made by Mr. J. E. Howard with the Emery testing-machine at Watertown Arsenal. The test bars were 0·79 inch diam., 5 inches long between the ends, and had screwed ends. The tensile strength diminished for all the bars as the temperature rises from 0° F. to a temperature between 200° and 300°, the temperature of minimum strength being lowest for the bars

with lowest carbon percentage. From this point of minimum strength the strength increases with rise of temperature till a maximum is reached at between 400° and 650°. From the point of maximum strength the strength diminishes as the temperature is further increased. The yield point generally decreases with increase of temperature.

Fig. 172 shows the variation of tensile strength for four bars having the following composition and strength when tested at about 70° F. :

Bar	Carbon per cent.	Manganese per cent.	Stress at yield point, tons per sq. in.	Tensile strength, tons per sq. in.	Elongation per cent.	Contraction per cent.
A	·97	·80	36·6	69·0	8·5	11·6
B	·57	·93	26·8	52·7	13·2	20·8
C	·37	·70	21·4	38·3	24·0	45·4
D	·20	·45	17·0	30·9	26·2	41·6

The coefficients of elasticity were found to decrease as the temperature increased.

Bar	Temperature	E in tons per sq. in.	Temperature	E in tons per sq. in.	Decrease of E in tons per sq. in. for each degree F. rise of temperature
A	80°	13,000	455°	12,400	1·6
B	80	13,400	465	12,550	2·2
C	68	13,300	475	12,300	2·4
D	74	13,050	470	11,900	2·6

A very elaborate research on the strength of steel at different temperatures has been made by Prof. Martens,[1] and an abridged translation has been published in the *Proc. Inst. Civil Engineers*, vol. civ. p. 209. The material for testing consisted chiefly of steel of three qualities, of approximately 23, 27, and 30 tons per sq. in. tenacity in the annealed condition. For temperatures up to 200° C. (400° F.) a bath of paraffin was used; for temperatures up to 600° C. (1,100° F.) a bath of lead or lead and tin. For low temperatures a zinc vessel with double walls was filled with ice and salt, giving a temperature of −20° C. (−4° F.). Arrangements were made for measuring the elastic extension by the mirror apparatus. The limit of proportionality is lowered as the

[1] *Mitth. aus den K. Techn. Versuchsanst. zu Berlin*, 1890, p. 159.

temperature rises, and even at 570° F. it is doubtful whether any true limit of proportionality exists. Starting from — 4° F., the tensile strength diminishes to about 150° F., then increases considerably to about 480°, and lastly falls rapidly till it is very small (about 6 tons per sq. in.) at 1,100°. The stress at the yield point falls almost regularly with the increase of temperature.

The coefficient of elasticity E also falls with increase of temperature, and more rapidly as the temperature increases. The ultimate elongation per cent. rises a little at first, then rapidly falls, reaching a minimum value at temperatures from 400° to 570°, and then very rapidly increases again as the temperature rises. The contraction of area goes through similar changes. At 570° the steel is more brittle than in the cold state.

218. *Resistance to Impact at Low Temperatures.*—Some experiments on the materials used in the construction of gun carriages in Austria have been made by Capt. Kuczera and Capt. Reinisch.[1] For transverse impact the test bars were 0·6 inch deep by 0·2 inch wide on supports 4 inches apart. Each test piece was nicked on the under side with a file. The blows were given by a weight of 8·8 lbs. falling 6 inches. The materials were subjected to impact at normal temperature (about 68° F.), and cooled to —4° F. in ice and salt. In every case an average of five tests was taken. It was found that for transverse impact the cooled bars broke with fewer blows than the bars at normal temperature. On the other hand, for longitudinal impact all the materials tested sustained more blows when cooled than at normal temperatures. Also the extensions before breaking were greater for the cooled bars than for those at normal temperature.

219. *Influence of very Low Temperatures on the Strength and Ductility of Iron and Steel.*—Prof. M. Rudeloff[2] made experiments on rivet iron, Siemens-Martin steel, wrought iron, spring steel, and cast steel at temperatures of 18°, —20°, and — 80° C. (65°, — 4°, and — 112° F.). The experiments show that both the stress at the yield point and the tensile strength are increased as the temperature is lowered. The ultimate extension is generally decreased by cooling. Spring steel and cast steel, which show no marked yield point at ordinary temperatures, have a well-marked yield point at — 112° F.

[1] *Proc. Inst. Civil Engineers*, cxii. p. 442.
[2] *Mitth. aus. den K. Techn. Versuchsanst. zu Berlin*, 1895.

In bending tests all the materials except wrought iron and rivet iron were prejudicially affected by cold. They cracked when bent through a smaller angle when cold than at ordinary temperatures.

V. Collection of Tables of the Results of Tests of Iron and Steel

In giving tables of the results of tests of iron and steel the object has been to select some of the most trustworthy results, on very various qualities of material, and to give them fully enough to permit some judgment to be formed of the range of quality in materials nominally the same. A very large and valuable collection of tests of iron and steel will be found in a treatise referred to below.[1] An abstract of these tables, giving merely mean values of very variable materials, would be of little use.

TENSION AND COMPRESSION

220. *Test of an Ancient Bloom of Scottish Iron.*—On the shores of Loch Maree in Ross-shire there are known to have been iron forges in operation towards the end of the sixteenth century. In 1892 Prof. Thorpe and Prof. Tilden obtained on this site a bloom about 16 inches in length, weighing about 12 lbs., and deeply corroded. Miss M. D. Dougal (*Trans. Chem. Soc.*, 1894) analysed the metal, and has given an account of it. It contained C, 0·192 per cent.; Si, 0·077; S, 0·012; Ph, 0·087; Mn, 0·038. A piece was planed out, and the author found it had a coefficient of elasticity = 13,600 tons per sq. in.; tenacity, 25·4 tons per sq. in.; yield point, 13·6 tons per sq. in.; ultimate extension, 10·5 per cent. in 10 inches.

221. *Mr. Harbord's Tests of Various Qualities of Steel.*—The following table gives a selection from a large number of tests of steel by Mr. Harbord.[2] The bars were about 0·7 inch diameter and were tested in two conditions, as rolled (R) and after heating to 620° C. (A) for twenty minutes. It appears that basic open hearth steel with 0·5 per cent. carbon has the same hardness as acid Bessemer steel with 0·4 per cent. carbon.

[1] *Die Eigenschaften von Eisen und Stahl.* Supplementband, Organ für die Fortschritte des Eisenbahnwesens. Wiesbaden, 1880.

[2] 'Relation between Process of Manufacture and Properties of Steel,' F. W. Harbord, *Iron and Steel Institute*, 1907.

TABLE VII. TESTS OF VARIOUS QUALITIES OF STEEL AS ROLLED AND ANNEALED (HARBORD)

Carbon, per cent.	Manganese, per cent.	Yield point, tons per sq. in. f_y		Breaking stress, tons per sq. in. f_b		$\frac{f_y}{f_b}$		Elongation in 6 ins. per cent.		Brinell hardness number	
		R	A	R	A	R	A	R	A	R	A
					Acid Bessemer						
·10	·51	14·7	14·5	26·8	26·0	0·55	0·56	24·3	25·0	100	96
·19	·49	18·4	18·1	32·9	31·1	0·56	0·58	22·8	23·1	108	107
·24	·90	19·7	19·8	34·6	34·2	0·57	0·58	23·4	23·8	111	111
·38	·87	24·6	22·5	41·5	41·0	0·59	0·55	19·6	16·9	131	128
·45	·88	27·2	22·1	46·5	42·6	0·58	0·52	17·3	15·0	139	135
·55	·86	26·9	23·0	51·9	44·6	0·52	0·44	14·0	14·3	151	147
·74	1·07	31·2	29·4	62·9	57·1	0·50	0·51	8·5	8·6	167	161
					Basic Bessemer						
·07	·35	13·3	14·3	23·5	23·4	0·57	0·61	30·3	27·9	76	81
·10	·44	14·6	15·0	25·5	24·4	0·57	0·61	28·6	28·0	84	82
·22	·51	17·3	18·9	31·5	29·8	0·55	0·60	24·0	24·7	102	100
·38	·86	20·1	20·5	39·5	37·8	0·51	0·54	18·7	17·9	120	117
·50	·90	26·3	26·8	48·0	46·4	0·54	0·58	6·8	7·0	143	141
					Acid Open Hearth						
·13	·40	13·6	12·3	25·5	25·4	0·54	0·49	29·2	30·6	82	78
·18	·71	13·2	15·6	30·3	30·2	0·43	0·52	27·2	27·7	98	96
·37	·80	16·6	17·5	37·0	35·6	0·45	0·49	21·8	22·0	119	111
·50	·67	23·1	22·8	45·8	44·1	0·50	0·52	15·6	15·1	142	137
·67	·60	29·5	26·6	55·7	52·2	0·53	0·51	7·6	9·3	172	161
					Basic Open Hearth						
·12	·40	12·3	13·5	24·5	24·2	0·50	0·56	23·0	29·7	78	78
·20	·51	14·9	15·2	28·5	27·4	0·52	0·55	23·6	24·2	85	80
·36	·90	17·7	16·5	34·4	32·1	0·52	0·52	22·1	18·1	106	104
·45	·72	22·5	22·8	42·5	40·1	0·53	0·57	14·3	15·1	120	118
·60	·71	26·6	26·1	51·5	49·2	0·52	0·53	8·3	9·4	141	136

222. *Report of the Steel Committee*, 1868–70.—The Committee made a series of experiments of a very interesting kind. They were experiments on bars of iron and steel of 10 feet length between the measuring points, a very exceptional length for test bars. The experiments were made in a chain-testing machine at Woolwich Dockyard. The specimens were placed in a trough 11 feet in length, with cross diaphragms at 12 inches apart, having a level planed V-groove to support the specimen. A V-cap was

TABLE VIII. TENSION AND COMPRESSION OF STEEL BARS (STEEL COMMITTEE)

($1\frac{1}{2}$ inch diameter. Measurements of extension and compression made on a length of 10 feet)

Mark	Make	Intended use	Tension			Contraction of area, per cent.	Ultimate elongation, per cent. in 120 inches	Compression	
			Mean extension per ton per in.	Yielding stress in tons per sq. in.	Ultimate stress in tons per sq. in.			Mean compression per ton per inch	Yielding stress in tons per sq. in.
S C	Crucible cast steel.	—	·000075	26·50	53·74			·000073	26·50
S C	,, ,, .	—	·000075	26·50	53·33	5·7	5·29	·000073	26·00
S C	,, ,, .	—	·000075	25·00	51·21			·000073	26·50
N B	,, ,, .	—	·000076	26·00	52·30			·000074	26·50
N B	,, ,, .	—	·000075	24·50	46·00	20·0	7·29	·000076	27·00
N B	,, ,, .	—	·000076	26·00	54·74			·000075	25·00
46	Cast steel .	tyres	·000076	26·00	43·48	5·2	4·74	·000071	25·50
H	,, .	piston rods	·000076	27·00	41·85	0·0	1·12	·000074	26·00
A	Crucible steel .	—	·000077	20·50	40·54	4·1	4·13	·000076	18·00
◇◇	,, ,, .	gun barrels	·000079	17·00	38·14			·000077	16·50
◇◇	,, ,, .	,,	·000078	17·00	39·61	4·3	7·95	·000076	16·00
◇◇	,, ,, .	,,	·000077	16·50	37·79			·000076	16·00
K A	,, ,, .	—	·000077	25·00	37·05	1·5	13·54	·000074	24·00
A A	,, ,, .	—	·000075	20·00	35·47	48·7	9·63	·000071	19·50
K	Bessemer steel .	—	·000077	19·50	35·61			·000073	17·00
K	,, ,, .	—	·000076	19·50	35·26	44·2	11·13	·000074	18·50
K	,, ,, .	—	·000077	19·50	35·34			·000073	18·50
31	Cast steel .	piston rods rolled	·000076	26·75	33·65	1·3	0·89	·000073	27·00
K B	Crucible cast steel.	,,	·000077	20·50	34·44	2·9	2·02	·000074	24·00
H	Bessemer steel .	—	·000075	19·50	34·09			·000076	22·00
H	,, ,, .	—	·000075	19·50	34·16	45·6	11·90	·000076	20·50
H	,, ,, .	—	·000074	21·00	34·33			·000076	21·00
S L W	,, ,, .	—	·000077	18·00	34·30			·000076	17·00
S L W	,, ,, .	—	·000078	17·00	33·07	19·2	11·48	·000074	15·00
◇	,, ,, .	tyres and axles	·000076	17·50	33·27			·000076	16·00
◇	,, ,, .	,,	·000078	16.00	34·05	41·2	13·61	·000076	15·50
◇	,, ,, .	,,	·000079	16·00	33·66			·000077	16·50

TABLE IX. TENSION AND COMPRESSION OF IRON BARS (STEEL COMMITTEE)

(1½ inch in diameter. Extensions and compressions measured on a 10-foot length of bar)

Mark	Make	Use	Tension			Contraction of area, per cent.	Elongation in 120 inches, per cent.	Compression	
			Mean extension per ton per inch	Yielding stress in tons per sq. in.	Ultimate stress in tons per sq. in.			Mean compression per ton per inch	Yielding stress in tons per sq. in.
L S	Lowmoor . .	—	·000076	14·00	27·80			·000074	13·50
L S	,, . .	—	·000076	14·00	29·53	5·9	7·01	·000075	13·50
L S	,, . .	—	·000077	14·00	29·33			·000075	13·00
L	,, . .	—	·000078	11·00	24·60			·000077	12·50
L	,, . .	—	·000078	12·50	25·72	48·8	12·65	·000077	10·50
L	,, . .	—	·000078	12·00	24·07			·000079	11·50
K C	Yorkshire . .	—	·000078	13·00	23·62			·000076	13·00
K C	,, . .	—	·000078	13·00	24·16	51·4	17·87	·000076	13·00
K C	,, .	—	·000080	13·50	23·29			·000077	—
F R	S. C. ♚ . .	—	·000083	11·50	22·48			·000079	11·50
F R	,, . .	—	·000081	11·50	22·48	47·7	17·50	·000080	11·50
F R	,, . .	—	·000078	12·50	22·92			·000082	12·00

fitted above and pressed down tightly by screws. Sliding verniers were placed on *both* sides of the bar, reading to $\frac{1}{10000}$ foot. It is probable that, from the great length in which the elongations and compressions were measured, and from the use of two symmetrical verniers, eliminating to a great extent the effect of initial bending, the measurements in these experiments were very trustworthy.

The experiments show that the stress at which the material yields is nearly the same for tension and compression. There are two other points very worthy of notice. The first is the great uniformity of mechanical properties within the elastic limit for all the bars, however diverse their mode of manufacture. The other is the much greater uniformity of the results of different tests of the same material than in the more ordinary tests of very short bars.

The compression and extension per ton per inch given in the tables are the mean values before yielding began.

223. *Tests of Iron Plates by Dr. Böhme.*[1]—Table X. contains a very complete series of tests of material, chiefly for boilers, made on similar test pieces. They are chosen partly because the measurements were made with great care.

TABLE X. TESTS OF IRON BOILER-PLATES (BÖHME)

(The test bars were $2\frac{1}{4}$ ins. wide, and $\frac{3}{8}$ to $\frac{9}{16}$ in. thick)

—	Thickness in inches	Stress in tons per sq. in.		Elongation, per cent.		Contraction of area, per cent.
		At yield point	At maximum load	In 8 ins.	In 4 ins.	
Tests in direction of rolling						
1 Boiler-plate .	·563	14·10	24·03	20·8	—	28·4
2 „ .	·559	15·62	26·42	20·8	—	22·3
3 „ .	·520	14·08	21·60	15·7	—	24·7
4 „ .	·508	16·15	25·35	19·0	—	29·7
5 „ .	·516	17·14	27·54	21·5	—	31·4
6 „ .	·516	17·00	25·11	17·3	—	23·8
7 „ .	·543	13·64	23·54	29·3	33·6	35·4
8 „ .	·539	14·21	23·97	29·6	33·9	33·2
9 „ .	·520	13·70	23·35	24·3	26·9	28·0
10 „ .	·386	14·27	21·95		—	—
11 „ .	·406	13·70	22·83	25·7	29·4	29·5
12 „ .	·398	13·83	22·65	22·5	25·6	—
13 „ .	·461	14·52	24·10	21·4	23·6	21·0
14 „ .	·461	13·90	22·84	15·4	—	—
15 „ .	·445	14·08	22·57	17·7	19·2	22·2
16 „ .	·449	16·68	26·04	—	21·0	—
17 „ .	·455	15·72	24·05	—	24·2	25·7

[1] *Mitth. aus den K. Techn. Versuchsanst. zu Berlin*, 1884.

TESTS OF IRON BOILER-PLATES—*continued*

—	Thickness in inches	Stress in tons per sq. in.,		Elongation, per cent.,		Contraction of area, per cent.
		At yield point	At maximum load	In 8 ins.	In 4 ins.	
18 „	·465	16·00	23·38	—	15·2	—
19 „	·465	15·66	24·18	—	25·1	26·7
20 „	·425	17·82	27·35	—	23·3	15·0
21 „	·465	15·82	23·75	—	24·2	33·1
$\frac{7}{16}$ Ship plate	·315	11·95	21·45	5·6	6·4	—
$\frac{7}{16}$ „	·315	13·20	24·93	11·4	12·6	17·0
$\frac{1}{2}$ „	·472	15·22	21·75	7·2	7·5	6·4
$\frac{1}{2}$ „	·472	15·60	21·75	5·7	6·4	6·6
$\frac{1}{2}$ „	·472	15·40	23·60	9·6	8·8	—
$\frac{7}{16}$ „	·394	15·66	24·23	5·7	6·2	4·0
$\frac{3}{8}$ „	·295	15·40	22·95	6·9	7·3	5·3
29 Harkort	·532	18·14	22·90	19·3	25·0	40·2
30 „	·521	17·70	22·83	21·3	27·9	45·1
31 Wohlert	·516	13·76	26·95	21·3	27·8	33·4
32 „	·557	16·18	25·25	18·7	23·4	29·0
33 „	·569	16·36	26·40	18·7	24·2	22·9
34 Boiler-plate	·500	16·06	24·74	—	—	—
35 „	·413	14·50	23·00	11·0	13·7	14·9
36 „	·394	17·44	25·80	19·3	22·6	19·6
37 „	·413	15·75	25·35	16·1	17·8	17·7
38 „	·398	14·78	24·35	—	25·5	27·6
39 Boiler-plate	·433	15·60	25·05	—	25·1	30·2
40 „	·421	17·70	25·57	—	25·3	24·9
41 „	·413	14·46	25·57	—	28·2	32·9
42 „	·449	18·20	25·70	24·3	28·6	29·1
43 „	·480	16·50	24·55	27·0	33·4	34·0
44 „	·476	16·18	24·48	25·4	28·2	30·6
45 „	·464	17·56	25·40	24·2	29·1	29·2
46 „	·472	14·46	24·23	23·4	30·9	31·5
47 „	·457	15·15	25·05	22·7	27·6	27·6
48 „	·464	15·40	25·45	23·9	29·8	30·8
49 „	·469	16·00	25·55	23·9	28·8	31·7
50 „	·469	14·84	25·50	23·5	28·2	30·8
51 „	·469	15·53	25·25	22·1	26·5	27·8
Tested across the direction of rolling						
1 Boiler-plate (Nos. 7–9 above)	·524	13·00	20·36	8·8	10·2	16·8
2 „	·524	13·06	21·75	12·8	15·9	15·1
3 „	·527	12·94	19·46	—	—	—
4 Boiler-plate (Nos.10–11 above)	·394	13·45	20·16	8·4	9·4	—
5 „	·364	14·08	19·84	7·8	8·2	9·6
6 „	·394	14·46	21·82	—	—	—
7 Boiler-plate (Nos.13–15 above)	·464	13·76	21·05	7·2	8·4	—
8 „	·464	13·35	20·18	7·4	7·6	10·2
9 „	·409	15·02	21·25	15·2	17·0	14·9
$\frac{7}{16}$ Iron plate	·315	14·33	21·95	7·4	7·6	—
$\frac{7}{16}$ „	·315	15·34	23·27	6·8	7·7	10·2
$\frac{1}{2}$ „	·472	15·34	20·42	4·4	5·0	1·7
$\frac{7}{16}$ „	·394	14·70	22·82	7·1	7·5	6·1

TABLE XI. TENSILE STRENGTH OF BASIC STEEL (GILLOT, 'PROC. INST. C. E.' LXXVII. P. 304)

Description	Section of ingot	Section of test piece in inches	Tenacity in tons per sq. in.	Elongation, per cent.			Contraction per cent.
				In 10 ins.	In 8 ins.	In 2 ins.	
Plate. .	12″×12″	2·015×·46	25·89	25·0	27·5	53·1	55·8
Axle . .	15″×15″	1″ diam.	22·29	31·3	34·1	53·1	62·9
Plate. .	12″×12″	2·03 ×·37	24·96	35·0	37·5	62·5	62·7
„ . .	15″×15″	1·99 ×·755	23·00	30·0	31·3	62·5	63·5
„ . .	15″×15″	2·035×·59	24·16	27·5	30·5	—	56·5
„ . .	19″×19″	1·52 ×·68	23·92	28·1	34·2	59·4	58·3
Billet from axle	19″×19″	1″ diam.	25·98	24·4	26·6	40·6	50·0
Plate. .	19″×19″	1·765×·69	26·68	23·8	25·0	43·8	46·6
„ . .	27″×12″	1·52 ×·705	26·68	26·8	28·5	53·1	49·8
„ . .	19″×19″	2·0 ×·565	24·07	28·8	31·3	50·0	48·9
Means .	—	—	24·76	28·0	30·6	53·1	55·5

TABLE XII. TESTS OF STEEL PLATES, ANNEALED AND UNANNEALED

Description of plates	Tenacity in tons per sq. in.	Elongation in 8 inches, per cent.
$\frac{1}{2}$-inch plate, hard steel, unannealed. .	32·97	16·65
„ „ annealed . .	28·52	24·12
$\frac{1}{4}$-inch plate, mild steel, unannealed .	26·60	24·32
„ „ annealed . .	24·05	29·87
$\frac{1}{2}$-inch plate, mild steel, unannealed .	28·55	25·05
„ „ annealed . .	26·95	26·90
$1\frac{3}{16}$-inch steel boiler-plate, unannealed .	28·25	21·25
„ „ annealed . .	25·75	28·75

TABLE XIII. SWEDISH STEEL

—	Tensile strength, tons per sq. in.	Elastic limit, tons per sq. in.	Elongation, per cent.
Steel for anchors . . .	32–34	14–18	20–25
„ boiler-plates . . .	22–31	13–18	22–32
„ loco. axles . . .	22–33	10–18	11–29
„ loco. frames . . .	24–30	16–19	23–28
Nickel steel, 1 per cent. Ni. .	40	21	12
2 „ „ .	50	28	11
4 „ „ .	61	29	7
Chrome steel, 1·5 „ Cr. .	70–76	30–34	2·5–6·0

TABLE XIV. THIN STEEL PLATES (UNWIN)

Thin steel plates are liable to get cold in rolling, and then the strength is increased and the difficulty diminished.

Series	Thickness in inches	Strength at yield point, tons per sq. in. p_y	Tensile breaking strength, tons per sq. in. p_b	Elongation in 8 ins. per cent. 100λ.	—
A	·13 to ·17	—	22 to 30	14 to 25	Sheet for riveted pipes
B	·14 „ ·20	14 to 24	25 „ 31	9 „ 27	„
C	·18 „ ·20	17 „ 23	26 „ 30	20 „ 26	„
D	·11 „ ·16	17 „ 24	24 „ 31	9 „ 14	„
E	·12 „ ·13	15·7 „ 16·6	21·5 „ 22·6	22 „ 26	Solid drawn pipe
F	·13	16·4 „ 19·3	23·5 „ 28·2	15 „ 26	Welded steel pipe
G	·23 to ·30	25 „ 31	29 „ 33	9 „ 10[1]	Gas cylinders[2]

224. *Nickel Steel.*—A material of greater strength than ordinary steel, which has found application for boilers, shafting, engine forgings, and in other cases. It has a high elastic limit, and corelative with this a high resistance to fatigue under variations of stress. Mr. Hadfield found that in steel containing 0·15 to 0·20 per cent. of carbon, the addition of nickel increased the mechanical properties to the following extent:

Nickel, per cent.	Elastic limit, tons per sq. in.	Tensile strength, tons per sq. in.	Elongation, per cent.	Contraction, per cent.
11·4	48·7	88·8	12	26
3·8	25·0	33·2	35	55

The Bethlehem Steel Company obtained the following results for forgings:

Composition		Elastic limit, tons per sq. in.	Tensile strength, tons per sq. in.	Elongation, per cent.	Contraction, per cent.
C	Ni				
0·2	0	21·5	24·8	34	60
0·2	3·5	21·4	37·9	26	55
0·3	0	16·5	33·5	30	50
0·3	3·5	26·8	42·4	22	48
0·4	0	19·2	37·9	25	45
0·4	3·5	32·2	49·2	18	40

[1] In four inches. [2] Cylinders for compressed gas.

225. *Special Steels.*—M. Leon Guillet has given the following data for some modern steels:

Table XV. Special Steels

—	Tenacity, tons per sq. in.	Elastic limit, tons per sq. in.	Elongation, per cent.	—
Nickel-Silicon (C, 0·22; Ni, 12; Si, 1·78)	107	90	9	Annealed
	129	88	4	Hardened
Nickel-Vanadium (C, 0·2; Ni, 7; V, 0·2)	41	29	20	Annealed
	89	76	10	Hardened
Nickel-ChromeVanadium (C, 0·45; Ni, 2·25; Cr, 0·6; V, 0·07)	44	32	20	Annealed
	95	83	6	Hard. and temp.
Nickel-Chrome (C, 0·173; Ni, 5·47; Cr, 0·18)	39	23	—	Annealed
	83	77	—	Hard. in oil

226. *The Testing of Rails.*—The testing of rails is of very great importance from the extent of the manufacture and the serious consequences which may follow the use of unsuitable material. Rail steel is commonly required to contain 0·35 to 0·50 per cent. of carbon; 0·7 to 1·0 per cent. of manganese, and not more than 0·07 per cent. of phosphorus. The tensile strength is usually specified as 40 to 48 tons per sq. in. with an elongation of 15 per cent. in bars of $\frac{1}{2}$ sq. in. area and 3-ins. gauge-length. The test most relied on is a falling weight test. For flat bottom rails, a piece 5 ft. long, placed on bearings 3 ft. apart for light rails to $3\frac{1}{2}$ ft. for heavy rails, is struck in the centre by a tup. The weight of tup varies from 5 cwts. with 8 ft. drop for rails weighing 20 lbs. per yard to 20 cwt., and 30 ft. drop for rails weighing 100 lbs. per yard. The blow must be sustained without fracture. For bull-headed rails, the impact test is somewhat differently arranged. The tup weighs 20 cwt., and two blows are given with different heights of fall. Limits of deflection for each blow are specified. Complete specifications for rails, with details of tests, have been published by the British Standards Committee and are easily obtainable.

Tetmajer[1] has made a considerable number of tests of rails, with a view of determining the connection between the bending test and the hardness of the rails. The pieces were 4·6 feet long, and were supported on bearings 3·28 feet apart. The supporting knife-edges and that of load shackle were rounded to a diameter of $1\frac{1}{8}$ inch. The quantities determined were the elastic limit in bending (or limit at which there was no measurable set), the deflection with 35 tons load, and the ultimate or breaking load; diagrams were constructed from which the work of deformation was calculated. The rails varied from 67 to 75 lbs. per yard. The moment of inertia of the sections varied from 21·5 to 25·1 (inch units). The table below gives the results on some of the rails from the Swiss Central Line, weighing 74 lbs. per yard, and 5·11 inches high. Moment of inertia of section, 24·8.

Table XVI. Experiments on Rails (Tetmajer)

—	67	52	51	60	54	56
Elastic limit in bending, tons	23·0	27·5	26·0	28·5	33·5	35·5
Breaking load, tons	41·0	39·8	39·7	47·7	45·0	51·2
Deflection at limit, inches	0·165	0·208	0·177	0·201	0·209	0·244
Deflection at 35 tons, inches	0·216	1·300	1·24	0·84	0·59	0·224
Deflection at breaking, inches	5·63	5·16	4·64	4·72	4·37	5·12
Work of deformation up to limit, inch-tons	1·92	2·88	2·32	2·84	3·48	4·32
Work of deformation up to 35 tons, inch tons	61·68	37·32	38·76	23·96	16·52	3·96

The variation of the deflection is much greater than the variation of the tenacity in tensile tests.

Tensile Tests of Rails.—The following tests were made by the author for a Committee of the Board of Trade. A number of worn rails were selected and a test bar, approximately of 0·5 sq. in. area, slotted out of the head, web, and foot of each. The elongations were measured in 8 inches or for $l = 11\sqrt{A}$ approximately. The yield points were determined from autographic diagrams.

[1] *Stahl und Eisen*, 1886, p. 408. *Proc. Inst. of Civil Engineers*, vol. lxxxvii. p. 480.

TABLE XVII. TENSILE TESTS OF RAILS (UNWIN)

No. of rail	Tensile strength, tons per sq. in.	Elongation in 8 ins. per cent.	Hardness No. (Unwin)	Carbon, per cent.	Manganese, per cent.
10	36·4	19·0	195	0·33	0·69
1	36·9	18·7	211	0·34	0·71
9	37·2	17·1	235	0·40	0·48
12	37·6	19·3	195	0·37	0·80
8	38·9	15·0	215	0·29	0·63
11	39·4	16·8	221	0·34	0·84
13	39·5	17·4	205	0·37	0·80
5	40·1	15·1	237	0·39	0·58
6	41·4	16·8	236	0·45	0·61
17	42·7	16·4	233	0·35	1·06
14	43·8	16·1	245	0·41	0·91
16	45·3	14·1	254	0·37	1·01
15	50·5	12·6	256	0·42	1·14

Transverse Tests of Rails.—Bending tests were made of the same series of rails. Each rail bar was supported on a span of 54 inches on cylindrical bearings, and loaded at the centre. The top of the rail was in tension. The test was continued till lateral bending began. The approximate elastic limit was determined from a plotting of the deflections, but its position was not well marked. An impression of the rail end was taken, and from this the area and moment of inertia of the section was obtained by planimeters. In the table the rails are arranged in order of hardness. These transverse tests do not give very definite information as to the quality of the rails.

TABLE XVIII. TRANSVERSE TESTS OF RAILS (UNWIN)

Carbon, per cent.	Sectional area, sq. ins.	Height, ins.	Moment of inertia, J	Distance y from N. A. to top of rail, ins.	Section modulus, Z	Stress at elastic limit, tons per sq. in. f_t	Coefficient of elasticity, E tons per sq. in.
·33	6·74	5·04	19·5	2·36	8·28	20·4	7,637
·37	7·34	5·14	22·1	2·43	9·11	18·5	6,506
·37	7·74	5·15	26·0	2·46	10·56	12·8	6,524
·34	7·16	5·03	21·9	2·53	8·64	15·6	7,530
·29	7·20	5·03	22·0	2·52	8·73	19·3	7,273
·34	7·14	5·15	21·2	2·47	8·58	11·8	9,059
·35	6·02	4·95	18·5	2·35	7·88	17·1	10,200
·40	7·08	5·10	21·8	2·53	8·61	19·6	8,015
·45	6·16	4·97	18·3	2·41	7·58	17·8	10,520
·39	7·70	5·19	24·3	2·62	9·28	21·8	9,177
·48	7·56	5·18	23·4	2·60	8·99	18·8	8,502
·41	7·80	5·35	25·3	2·46	10·28	13·1	9,696
·54	7·64	5·12	22·7	2·48	9·17	18·4	7,920
·54	7·86	5·18	24·2	2·49	9·70	17·4	9,170
·37	6·60	5·05	19·9	2·34	8·50	19·9	8,231
·41	7·68	5·40	25·8	2·45	10·51	22·5	8,696

EXPERIMENTS ON SHEARING AND TORSION

227. *Shearing Strength.*—Let fig. 173 represent a portion of iron or steel plate, the large arrow indicating the direction of rolling. Then there are six directions in which the plate can be sheared, differently placed with reference to the structure developed by rolling. In the course of an inquiry into the causes of a boiler explosion at Augsburg, Bauschinger experimented on the shearing resistance of wrought iron in all these directions.[1] The test bar was a rectangular block, fixed in the machine between two cutting edges, and sheared in single shear. The shearing was sometimes sudden, with a loud crack, sometimes more gradual. In directions I. and II. the sheared surfaces were laminated, or scaly; for the directions III. and IV., fibrous; in the directions V. and VI., irregularly torn. The following are the mean values obtained:

TABLE XIX. SHEARING RESISTANCE OF IRON AND STEEL (BAUSCHINGER)

Description of plates	Shearing resistance, in tons per sq. in., in the directions					
	I	II	III	IV	V	VI
Iron:						
Plates from exploded boiler at Augsburg	16·50	16·64	18·91	19·80	8·46	8·44
Puddled plate (Leon Magis & Co.)	17·18	16·25	20·20	19·10	10·30	10·33
Puddled plate (Leon Magis & Co.) annealed	18·36	17·84	19·68	19·68	8·89	9·20
Charcoal plate . . .	17·78	17·30	20·16	20·00	9·20	8·06
German Lowmoor plate .	18·64	17·60	22·05	21·95	10·05	9·17
Rolled iron bar . . .	22·15	17·16	22·55	19·00	11·70	10·15
Rolled iron bar, annealed .	21·20	19·68	23·23	20·25	10·60	13·27
Plates from exploded boiler at Wurtzburg, from uninjured plate	15·42	15·06	17·62	17·68	6·95	7·23
Plates from exploded boiler at Wurtsburg, from injured plate	14·40	14·38	17·26	16·28	5·20	4·76
New locomotive plate . .	16·00	16·38	19·10	19·90	10·01	9·58
Cast steel:						
Bessemer plate . . .	24·12	23·42	26·45	27·35	22·90	21·45
„ „ . . .	26·30	26·40	29·20	29·20	25·05	25·70

[1] *Mittheilungen.* München, 1874.

Mr. Izod's Shearing Tests.[1]—Mr. Izod, using a shackle previously described, made a series of tests on resistance to shear. He aimed at obtaining a condition of 'pure shearing

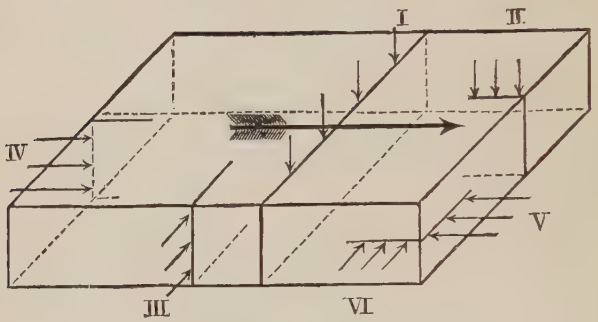


Fig. 173.

stress,' but it is doubtful if it is possible to get more than an approximation to that condition.

Material	Tensile strength, tons per sq. in.	Elongation, per cent.	Shearing strength, tons per sq. in.
Wrought iron bar . . .	26·0	22·5	19·4
Mild steel plate . . .	26·9	34·7	21·0
Swedish crucible steel :			
0·12 Carbon . .	24·9	43·0	18·5
0·48 „ . .	42·1	26·0	28·8
0·71 „ . .	56·3	15·0	36·6
0·77 „ . .	61·3	11·0	38·3

228. *Torsional Strength.*—The following are mean values of torsional tests, made by Messrs. Platt and Hayward at the engineering laboratory of University College.[2] For comparison, values of the tenacity and shearing strength from direct experiments on tension and shearing of the same materials are also given :

[1] *Proc. Inst. Mech. Eng.*, 1905.
[2] *Proc. Inst. Civil Engineers*, vol. xc. p. 382.

TABLE XX. TORSIONAL STRENGTH OF IRON AND STEEL (PLATT AND HAYWARD)

Material	Limit of elasticity in tons per sq. in.	Calculated shearing stress at fracture in tons per sq. in.	Final twist in revolutions in 9-inch length	Coefficient of rigidity in tons per sq. in.	Tenacity in tons per sq. in.	Ultimate shearing stress, from shearing tests, in tons per sq. in.
Wrought iron, Crown best	8·99	25·2	8·90	5,714	21·60	18·76
Bessemer steel	20·28	44·64	3·84	5,750	52·20	35·21
Crucible steel	19·36	42·30	4·36	6,098	52·16	33·30
Landore rivet steel, 0·18 carbon 0·6 manganese	10·20	29·85	7·85	5,834	28·40	23·00
Crown rivet iron	10·36	28·87	6·90	6,116	25·01	21·21
Steel cut from casting	10·40	34·7	4·15	5,822	38·04	27·60
Siemens - Martin steel	10·16	28·13	9·92	5,981	25·75	20·94
Wrought iron, S.C. Crown	10·22	29·5	7·45	6,213	24·56	20·75

The apparently high shearing stress in the torsion experiments is no doubt due to the false assumptions involved in the formula for torsional resistance when applied to stresses at rupture.

VI. STEEL CASTINGS

229. Steel castings are now largely used, sometimes in place of cast iron and sometimes instead of forgings. Roughly, they are usually assumed to have nearly double the strength of cast iron. Tests, however, show wide divergence both as to strength and ductility. The steel melts at about 3,500° F., a temperature much higher than that of cast iron. Consequently, the contraction of the castings is nearly double that of cast iron. To obviate danger from this contraction annealing is necessary, and in some cases the casting is removed from the mould as soon as set, and placed in an annealing furnace, kept at a temperature of 1,700° F., for not less than 24 hours. Hardening in oil and annealing afterwards improves the strength, and still more the ductility, of the casting, the effect being similiar to that of forging. Unannealed castings may have a strength of 24 tons, with 1 to 5 per cent. of elongation; annealed, a strength of 27 to 30 tons, with 3 to 8 per cent. of elongation; hardened and again

annealed, a strength of 27 tons, with 20 per cent. of elongation, or 36 tons, with 12 per cent. elongation.[1]

The amount of carbon varies from 0·25 to 1 per cent.; a small amount of phosphorus makes the casting sounder. The manganese varies from 0·3 to 0·7 per cent. Silicon, added, just before casting, in quantity depending on the amount of carbon, prevents ebullition of gas during solidification.[2]

Table XXI., from Mr. Hill's paper, shows the effect of annealing:

Table XXI. Influence of Annealing on Steel Castings (Hill)

Tenacity in tons per sq. in.		Extension in 5 ins. per cent.		Contraction of area per cent.	
Not annealed	Annealed	Not annealed	Annealed	Not annealed	Annealed
33·79	32·80	12·00	22·00	8·16	38·70
32·10	36·60	4·16	14·60	2·90	28·11
—	32·30	—	15·00	—	38·70
24·01	28·40	1·00	13·00	2·80	15·90
—	30·08	—	21·90	—	23·05

Valuable experiments on the strength of steel castings have been made by Mr. H. Foster, of Newburn Steel Works:[3] (Table XXII.)

Table XXII. Properties of Steel Castings as Dependent on Composition (Foster)

No. of test	Composition, per cent.			Tenacity in tons per sq. in.	Elongation per cent., in 1·75 in.	Contraction of area, per cent.
	Carbon	Silicon	Manganese			
1	0·30	0·22	0·63	31·0	24·0	43·8
2	0·30	0·22	0·63	30·4	24·0	43·8
3	0·30	0·22	0·63	33·4	24·0	41·0
4	0·35	0·23	0·61	33·0	22·2	41·0
5	0·35	0·23	0·61	36·0	21·5	37·1
6	0·50	0·40	0·66	44·0	12·0	16·8
7	0·50	0·40	0·66	45·2	5·0	6·3
8	0·50	0·40	0·66	42·2	9·0	12·3
9	0·77	0·46	0·67	39·8	1·0	1·4
10	0·77	0·46	0·67	39·8	1·9	3·3
11	0·77	0·46	0·67	33·6	1·5	1·8
12	0·96	0·62	0·64	31·0	2·0	2·2
13	0·96	0·62	0·64	38·0	1·0	0·8
14	0·96	0·62	0·64	35·6	1·0	1·8

[1] Considère, *L'Emploi du Fer.*
[2] Hill, *Proc. Inst. Civil Engineers*, vol. xc. p. 359.
[3] *Proc. Inst. of Civil Engineers*, vol. xc. p. 365.

Some experiments by the author on steel castings, turned to ordinary test bars about 1 inch in diameter, gave results, shown in Table XXIII. below. Fig. 174 gives autographic diagrams for some of the bars.

TABLE XXIII. TESTS OF STEEL CASTINGS (UNWIN)

Test No.	Diameter in inches	Tenacity, tons per sq. in.	Extension, per cent.		Contraction of area, per cent.	Coefficient of elasticity, tons per sq. in.
			In 10 ins.	In 8 ins.		
162	·997	16·26	0·61	—	0·76	10,930
163	·997	13·05	0·30	—	0·38	14,050
164	·620	15·07	—	0·37	0·60	9,138
165	·615	19·86	0·68	—	—	9,972
166	·619	20·53	—	0·75	—	10,220
167	·621	14·52	—	0·25	—	8,384

There were flaws in the fractured sections of 163, 164, and 166.

Strength of Steel Castings at Different Temperatures.—Rudeloff found the following values:

Temperature C. . . .	Ordinary	100	200	300	400	500
Tenacity, tons per sq. in. .	25	28	33	32	28	13
Elongation, per cent. . .	28	15	27	25	36	64

Mitis Castings.—These are castings of wrought iron to which about 0·05 to 0·1 per cent. of aluminium has been added. The aluminium lowers the fusing point of the iron 300° or 400°. The furnace used is a petroleum furnace, and the iron is melted in crucibles of plumbago or of fireclay. The tenacity is said to be 20 per cent. greater than that of wrought iron, and the ductility about equal to that of wrought iron.

230. *Strength of Wire.*—Wire is stronger than the material out of which it is made, in consequence of the greater amount of mechanical work expended on it. When in the condition in which it leaves the draw-plate it is virtually 'cold rolled.' Annealing reduces this excess of strength.

The following results are taken from a paper on the effect of rolling and wire-drawing by Mr. Horace Allen.[1] They show the changes in strength and ductility of the same steel, in the original billet, after rolling down into wire rod and after drawing into wire. Also the difference of strength and

[1] *Proc. Inst. Civil Engineers*, vol. xciv. p. 235.

ductility in the unannealed (bright) and annealed (black) condition. The original billet of steel was 2 inches square in section, and contained carbon 0·115, phosphorus 0·072, manganese 0·410. A test bar made from a portion of the billet was rolled into rods of No. 1, No. 2, and No. 5

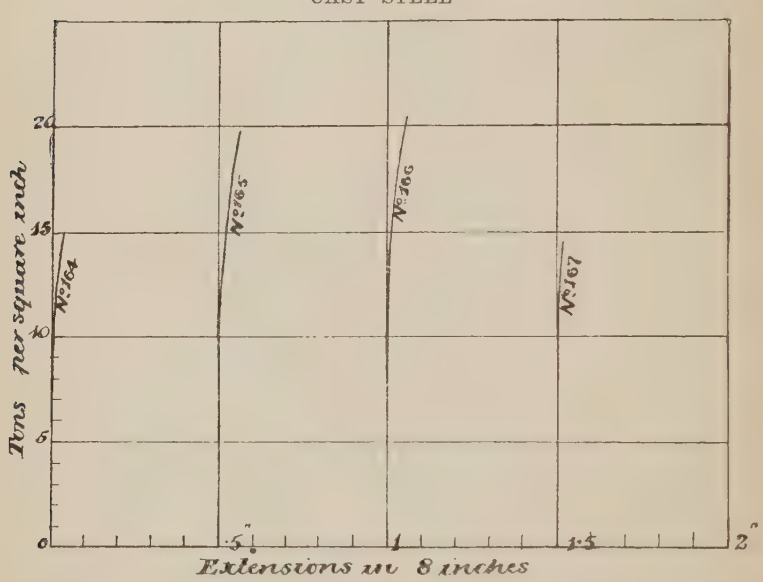


FIG. 174

B.W.G. size. Portions of these rods were tested and other portions drawn into wire.

—	Size B.W.G.	Diam. in.	Area sq. in.	Elastic limit, tons per sq. in.	Tensile strength, tons per sq. in.	Elongation per cent. in 8 ins.
Billet	—	1·12	0·985	17·0	28·1	28·1
Wire rod	No. 1	0·31	0·075	22·4	32·1	21·3
„ (annealed) . . .	No. 1	0·31	0·075	21·4	30·3	22·8
Wire drawn from No. 1 rod .	No. 3	0·25	0·047	27·5	48·8	1·9
„ (annealed) . . .	No. 3	0·25	0·047	—	27·1	15·2
Wire rod	No. 2	0·27	0·057	20·0	29·8	21·1
„ (annealed) . . .	No. 2	0·26	0·053	20·4	28·8	19·8
Wire from No. 2 rod . .	No. 4	0·23	0·042	30·1	44·1	3·2
„ (annealed) . . .	No. 4	0·23	0·042	19·9	27·7	17·5
Wire rod	No. 5	0·21	0·035	25·4	31·7	18·8
„ (annealed) . . .	No. 5	0·20	0·032	20·9	29·5	21·6
Wire from No. 5 rod . .	No. 8	0·16	0·020	47·3	56·4	1·0
„ (annealed) . . .	No. 8	0·16	0·020	18·8	26·6	21·2

The following table gives a few miscellaneous tests of the strength of wire made by the author:

—	—	Diameter ins.	Area, sq. ins.	Tenacity tons per sq. in.	Extension in 8 ins. per cent.
109	Black shear-steel rod . .	·194	·0296	50·90	7·0
110	,, ,, . .	·192	·0289	52·52	6·25
103	Black soft-steel wire . .	·196	·0302	39·17	11·25
102	,, ,, . .	·196	·0302	38·07	15·6
106	Bright hard steel rod . .	·197	·0305	51·96	7·5
107	,, ,, . .	·198	·0308	51·45	6·5
—	Plough wire . . .	·080	·0050	111·9	1·0
—	,, ,, . . .	·065	·0033	114·4	1·4
—	,, ,, . . .	·049	·0019	125·4	1·0
—	Piano wire . . .	·0865	·0059	124·9	1·15
—	,, ,, . . .	·065	·0033	130·0	1·25
—	,, ,, . . .	·050	·0020	118·2	1·85

CHAPTER XV

COPPER, COPPER ALLOYS, AND MISCELLANEOUS TESTS OF METALS

231. *Copper.*—This is a deep red metal of great ductility, and, relatively to most metals except iron, of great tenacity. Its density is 8·6 to 8·9 when cast, 8·8 to 8·9 when rolled. It weighs on the average 546 to 552 lbs. per cubic foot. Its fusing point is about 2,000°. Its tenacity when cast is about 8½ to 12 tons per sq. in. Hammering or rolling increases its strength at the expense of its ductility, but the ductility is restored by a process of annealing. Copper is annealed by heating to cherry red, allowing it to cool to dull red, and then quenching in cold water. Phosphorus is added to facilitate casting, and the strength is greater the larger the percentage of phosphorus used. The phosphorus reduces the oxides formed in melting the alloy.

The table below gives some of the most trustworthy results on the strength of copper:

Description of material	Tenacity in tons per sq. in.	Authority
Forged copper	15·2	Anderson
„ 0·015 phosphorus . . .	17·0	„
„ ·02 „ . . .	20·1	„
„ ·03 „ . . .	21·4	„
„ ·04 „ . . .	22·3	„
Ingot copper	11·6 to 13·3	Thurston
Cast „	6·5 „ 9·2	„
Rolled „	12·9 „ 14·3	Bauschinger [1]
„ „ ½-in. thick	13·3 „ 14·2	Unwin [2]

The coefficient of elasticity of cast copper is given as 4,460 to 6,700 (Thurston); that of hard-drawn wire as

[1] Contraction of area, 30 to 45 per cent.
[2] Extension in 8 inches, 20 to 43 per cent.; mean, 37 per cent.

7,650, and of annealed wire 6,680 to 7,650 tons per sq. in. (Wertheim).

The coefficient of bending strength is 8·9 to 17·8 tons per sq. in. for cast copper, and reaches 26·7 for rolled copper (Thurston).

Fig. 175 gives autographic diagrams of copper. The highest diagram is a normal diagram for rolled copper. The other diagrams are for the same copper, heated, and allowed to cool.

232. *Investigation of the Strength of Copper at the Versuchsanstalt at Berlin.*—A very complete investigation has been carried out by Prof. Martens.[1] Experiments on the softening

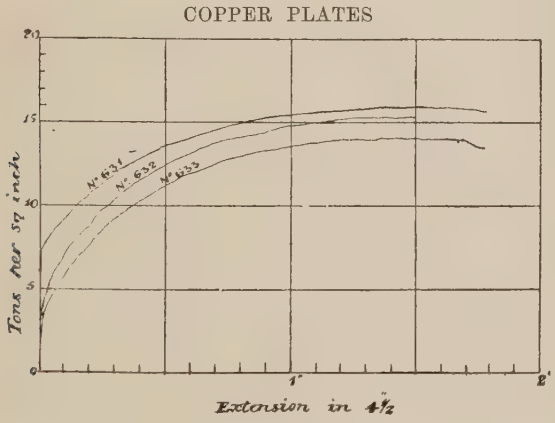


Fig. 175.

of hard-drawn copper by heating and cooling in water showed that heating to 300° C. produces a perceptible effect, and that at 400° C. the softening is almost complete. Repeated heatings to 350° C. completely soften the copper.

The increments of extension for given increments of load are greater for the first loading than for subsequent loadings. There is no proportionality between stress and strain even in repetitions of loading. Permanent set occurs with both hard and soft copper at very low stresses. The rate of loading does not affect the breaking stress, and has a very small

[1] *Mitth. aus den K. Techn. Versuchsanst. zu Berlin*, 1894. There is an abstract of this report by Mr. C. H. Moberly in *Proc. Inst. Mech. Eng.*, 1895, p. 658.

effect on the extension and contraction of area. The law of similarity of deformation in bars of similar form was verified; that is, the percentage of ultimate extension was found to be the same in bars of different section, when the extension was measured on a length proportional to the square root of the sectional area. It is recommended that the extension should be measured on a length equal to $11{\cdot}3\sqrt{}$ (area of section). Hammering the test strips raises the yield point to four or five times its value for the copper in its normal state, but raises the breaking stress only slightly. The extension is greatly diminished. When annealed, the copper is brought back almost completely to its initial condition. In annealing, it is desirable that a temperature of 500° C. should be reached.

233. *Tin* is chiefly valuable in engineering for alloying with copper to form bronze. Its density is 7·3 to 7·4 (weight about 456 lbs. per c. ft.). Thurston gives its tenacity as ranging from 0·89 to 2·68 tons per sq. in., and its coefficient of elasticity as ranging up to 3,125 tons per sq. in.

Zinc, known also as spelter, is used for alloying with copper to form brass. It is malleable within narrow limits of temperature, and can be rolled into sheets for roofing. It fuses at 750° to 930°. Clean iron immersed in melting zinc gets a protective coating, the process being termed galvanising. The zinc being electro-positive protects the iron from oxidation, and its own oxide is insoluble in water. If, however, sulphuric acid is present, a sulphate is formed, and the zinc coating perishes. The tenacity of cast bars is 2·0 to 2·9 tons per sq. in. (Thurston). The author found a tenacity of 1·1 to 1·5 ton per sq. in. Cast zinc breaks without sensible elongation or contraction. Trautwine gives for sheet zinc a tenacity of 7·14 tons per sq. in., and for wire 9·8 tons per sq. in. Wertheim gives the coefficient of elasticity as 5,360.

Lead is a valuable metal for certain purposes, from its great ductility. Its density is 11·4 (711 lbs. per c. ft.). It fuses at 620° F. In testing it contracts in section very much. Its tenacity is about 1·1 ton per sq. in., reckoned on the original area of the bar.

234. *Alloys.*—An extensive investigation of the properties of alloys was made by Professor Thurston[1] for the United

[1] *Report of the United States Testing Board*, vol. i. 1878. Also *Materials of Engineering*, Thurston, Part III.

States Testing Board. As to the general properties of an alloy Professor Thurston says, 'The physical properties of an alloy are often quite different from those of its constituent metals. In most cases, however, the hardness, tenacity, and fusibility will be greater than the mean of the same properties in the constituents, and sometimes greater than in either; while the ductility is usually less, and the density sometimes greater, sometimes less. The colour is not always dependent upon the colours of the constituent metals, as is shown by the brilliant white of speculum metal, which contains 67 per cent. of copper.'

BRONZES

235. *Bronzes* are alloys of copper and tin. With a moderate amount of tin the alloy is tough and strong. With more than 20 per cent. of tin it becomes weak and brittle. Up to 17½ per cent. of tin the elastic limit, according to Thurston, lies between 0·5 and 0·6 of the breaking strength. With 25 per cent. it rises up to the breaking weight. With more than 40 per cent. it falls again till it reaches about 0·3 of the breaking strength of pure tin.

Gun-metal for bearings may contain 88 to 95 per cent. of copper. Gun-metal for guns contains usually 90 per cent. Bell-metal contains 72 to 82 per cent., and speculum metal 67 to 75 per cent. The following table gives values of the tenacity with different proportions of tin:

Composition		Description	Tenacity, tons per sq. in.	Authority
Copper	Tin			
92·0	8·0	Gun-metal	12·95	Anderson
91·7	8·3	,,	13·84	,,
91·0	9·0	,,	14·73	,,
90·0	10·0	,,	16·96	,,
84·3	15·7	Bell-metal	16·1	Mallet
82·8	17·2	,,	15·2	,,
81·1	18·9	,,	17·7	,,
79·0	21·0	,,	13·6	,,
76·3	23·7	,,	9·7	,,
73·0	27·0	,,	4·9	,,

The following table gives a reduction of those of Thurston's results which relate to the more useful bronzes:

Composition[1]		Density	Coefficient of bending strength, tons per sq. in.	Coefficient of elasticity, tons per sq. in.	Tenacity, tons per sq. in.	Elongation in 5 ins. per cent.
Copper	Tin					
96·27	3·73	8·65	14·83	6,132	14·29	14·29
92·8	7·2	8·69	19·52	6,368	12·74	5·53
92·5	7·5	8·68	17·26	6,063	12·46	7·43
90·0	10·0	8·67	22·05	6,255	11·99	3·66
87·5	12·5	8·65	26·96	5,568	13·88	3·56
86·57	13·43	8·68	—	—	13·14	3·33
82·5	17·5	8·79	30·32	6,762	16·16	0·71
80·0	20·0	8·74	25·32	5,938	14·72	0·40

The bars for bending were 1 inch square and 22 inches between supports. The test bars for tension were about $\frac{3}{4}$ inch in diameter.

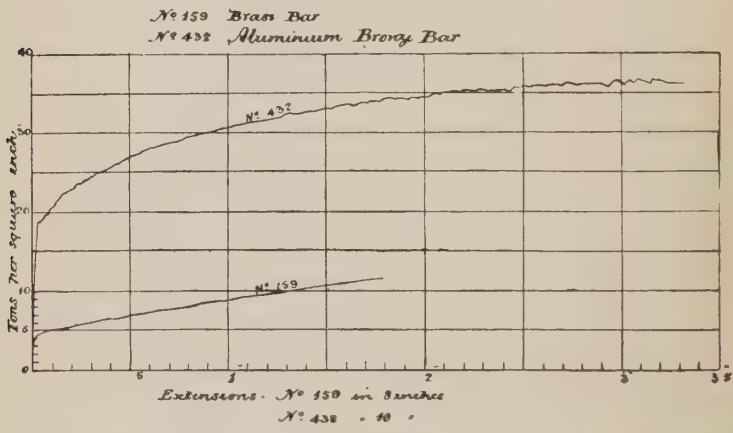


Fig 176.

Rolled or drawn bars of bronze are produced of tenacity from 20 to 42 tons per sq. in. with elongation of 15 to 25 per cent. in bars of $\frac{1}{2}$ sq. in. and 3 in. gauge-length.

236. *Brass* is an alloy of copper and zinc, sometimes with a little lead added. Ordinary brass contains from 66 per cent. copper and 34 per cent. zinc, to 70 per cent. copper and 30 per cent. zinc. Muntz metal, which can be rolled hot, contains 60 per cent. copper and 40 per cent. zinc, or sometimes 66 per cent. copper, 33 per cent. zinc, and 1 per cent. lead.

[1] From original mixing, not analysis.

Mallet obtained the following values for the tenacity of brass :

Copper	Zinc	Tenacity in tons per sq. in.
90·7	9·3	12·05
87·7	12·3	13·37
85·4	14·6	14·28
83·0	17·0	13·83
50·0	50·0	8·93

The author obtained for ordinary brass used for machinery a tenacity of 10·43 to 11·62 tons per sq. in., an extension of 13 to 22 per cent. in 8 inches, and a contraction of area of 16 to 27 per cent. The coefficient of elasticity is about 5,080 for rolled brass.

Rolled or drawn bars of brass have a tenacity of 20 to 26 tons per sq. in., and in test bars of ½ sq. in. area and 3 ins. gauge-length elongations of 25 to 30 per cent.

The table below gives a selection of Thurston's results for brasses. The test bars were similar to those for the bronzes already described :

Composition		Density	Coefficient of bending strength, tons per sq. in.	Coefficient of elasticity, tons per sq. in.	Tenacity, tons per sq. in.	Elongation, in 5 ins. per cent.
Copper	Zinc					
82·5	17·5	8·63	10·35	6,440	14·55	26·7
80	20	8·60	9·46	5,567	14·59	31·4
75	25	8·53	9·97	5,985	13·62	35·8
70	30	8·44	10·92	6,265	13·62	29·2
65	35	8·37	12·70	6,175	16·88	37·7
60	40	8·41	17·40	5,461	18·33	20·7
55	45	8·28	18·95	4,258	19·77	15·3
50	50	8·29	14·94	5,167	13·84	5·0
45	55	—	21·63	6,261	10·78	0·8

The great change in the character of the alloy when the zinc exceeds 45 per cent. is best marked in the tension results. The coefficient of bending strength is calculated from the load which deflected the bar 3½ inches, or which broke it within that limit. Fig. 176 gives an autographic diagram for brass.

237. *Delta Metal.*—Mr. Dick has discovered a method of obtaining copper-zinc alloys combined with a definite percentage of iron, which have remarkable strength and

ductility. Iron is dissolved in melted zinc till the zinc is saturated. This iron-zinc alloy is then used in proper proportions in making brass. To prevent oxidation in remelting and the resulting variation of quality, a small amount of phosphorus is added, in combination with copper. The density of delta metal is 8·4; its melting point 1,800°. It can be worked hot and cold. It can be brazed. Cast in sand, it has a tenacity of about 21 tons per sq. in. Forged at a dark red heat the tenacity is 33 or 35 tons per sq. in. Hammered cold its tenacity is 40 tons per sq. in.

Tests of Delta Metal, supplied by Mr. Dick (Unwin)

Material	Elastic limit, tons per sq. in.	Tenacity, tons per sq. in.	Elongation per cent. in 8 ins.	Contraction of area, per cent.	Coefficient of elasticity, tons per sq. in.
Cast bar	8·89	23·79	7·74	11·93	5,052
„	7·38	16·73	9·80	15·42	5,503
„	7·47	17·05	8·10	5·90	7,021
Hexagon titled bar . .	10·65	29·22	12·15	18·44	6,423
Rolled bar	22·91	33·26	11·10	50·40	5,945
Ring cast while rotating .	—	23·47	25·8	21·1	—
Ring cast while rotating, hammered cold . .	—	39·75	—	—	—

238. *Aluminium.*—By the aid of electrical processes of reduction aluminium is now produced in large quantities at a price not differing greatly per lb. from double the price of copper. Commercial aluminium is never quite pure, the impurities being chiefly silicon and iron. The density of the pure metal is 2·58. Commercial metal is a little heavier, about 2·65–2·75. The fusing point is about 700°, varying with its purity. It is malleable like silver, and easily drawn into wire. It alloys easily with most metals.

Aluminium itself is not very strong or hard. To make it harder and stronger it is alloyed with some suitable metal. With a small percentage of alloying metal a product is obtained not much heavier than aluminium itself. On the other hand, if a small amount of aluminium is alloyed with a large amount of copper or other metal, heavy aluminium brasses or bronzes are obtained, some of them of great strength and ductility.

The following are some results with aluminium commercially pure, or with a small amount of alloy:

—	Coefficient of elasticity, tons per sq. in.	Tensile strength, tons per sq. in.	Ultimate extension, per cent.	Authority
Aluminium, cast . .	3,448	4·14	7 in 6″	Unwin
,, ,, . .	3,740	5·40	5·6 in 8″	Carpenter
,, ,, . .	3,700	6·44	5·3 in 11″	Inst. Technology, Boston
,, ,, . .	3,860	5·13	3·4 ,,	,, ,,
,, rolled .	4,550	6·39	16·5 ,,	,, ,,
,, ,, . .	4,600	7·28	9·1 ,,	,, ,,
,, ,, . .	4,270	10·45	5·7 ,,	,, ,,
,, ,, . .	4,630	10·20	10·2 ,,	,, ,,
,, squirted .	—	6·32	14 in 8″	Unwin
,, with tungsten	—	21·10	3 ,,	,,
Al 93, Cu 7, cast . .	5,700	8·10	1·1 in 11″	Inst. Technology, Boston
,, ,, . .	4,050	5·20	0·6 ,,	,, ,,
,, ,, . .	4,100	5·90	0·6 ,,	,, ,,
,, ,, . .	4,450	7·70	0·6 ,,	,, ,,
Al 94, Cu 6, cast . .	4,196	6·26	1·2 in 8″	Unwin
Al 93, Cu 7, cast . .	4,950	8·30	1·7 ,,	Carpenter
Al 96, Cu 4, rolled .	4,670	10·30	3·6 ,,	,,
Al 96·5, Cu 2, Cr. 1·5 .	4,400	11·70	1·3 ,,	,,

The heavy alloys in which the percentage of aluminium is small are of a different character. A copper-nickel aluminium alloy, termed Hercules metal, broke without sensible elongation at 44·6 tons per sq. in. But other alloys are very ductile.

Aluminium bronzes made at Neuhausen by the Heroult process have been tested by Professor Tetmajer at Zurich with the following results:

Grade	Per cent. aluminium	Tensile strength, tons per sq. in.	Elongation, per cent.
A	7	22·0–24·6	25–27
B	7½	24·4–26·0	25–27
C	8	23·2–31·0	34–48
D	8½	30·5	37·5
E	9	32·2–32·8	33–39
F	9½	33·2–35·6	16–24
G	10	35·2–39·4	11–19
H	10½	37·4–40·5	6–12

Two very important researches on aluminium copper and on aluminium copper manganese alloys have been carried out at the National Physical Laboratory. (*Proc. Inst. Mech. Engineers,* 1907 and 1910.)

Tenacity of Metals at Different Temperatures (Admiralty)

T = Loads in lbs. on testing-machine lever: D = Ductility; constant of testing-machine, 50·25
The actual tensile strength of the samples is found by multiplying the figures in columns T by 50·25

Temperature, Fahr.	Gun-metal rods, 1 in. diam.												Phosphor-bronze rods, 1 in. diam.		Muntz metal rods, ·74 in. diam.		Copper rods, ·72 in. diam.	
	1 Copper 87·75 Tin 9·75 Zinc 2·5		2 2nd set Copper 87·75 Tin 9·75 Zinc 2·5		3 Copper 91 Tin 7 Zinc 2		4 Copper 85 Tin 5 Zinc 10		5 Copper 83 Tin 2 Zinc 15		6 Copper 92·5 Tin 5 Zinc 2·5		Copper 92·5 Tin 7 Phos. 0·5		Copper 62 Zinc 38			
	T	D	T	D	T	D	T	D	T	D	T	D	T	D	T	D	T	D
Atmospheric	535	12·5	575	8·75	525	16	525	21	485	26	562	20	609	17·5	700	2·5	460	2·5
100°	505	10	—	—	525	15·5	550	18	480	26	—	—	614	17	680	2·5	465	2·5
150°	525	11	—	—	525	14	530	19·5	450	25·5	—	—	610	18	720	3·9	445	4
200°	485	10	535	8·75	460	9	523	19	460	26·25	440	11	605	18	685	3·9	440	5
250°	505	10	385	5	255	3	515	16	440	26	360	6	580	15	670	5	430	7
300°	500	10	295	0·66	265	Nil	531	18·25	435	23	255	0·66	575	12	650	2·5	430	6
350°	450	8·25	295	Nil	—	—	495	17	435	25	—	—	470	7	650	2·25	430	6
400°	245	0·75	—	—	260	Nil	260	2	435	25	—	—	424	5	600	2·25	420	6
450°	265	Nil	—	—	—	—	250	2	152	1·2	—	—	380	4	615	3·75	415	6
500°	250	Nil	—	—	275	Nil	230	2	152	Nil	—	—	420	5	620	5	390	6

239. *Strength of Copper at Different Temperatures.*—Old experiments by a Committee of the Franklin Institute show that the tenacity of copper diminishes with increase of temperature. The following are some of the results:

Temperature, Fahr.	Tenacity, tons per sq. in.	Temperature, Fahr.	Tenacity, tons per. sq. in.
122°	14·73	801°	8·48
302°	13·84	1,016°	4·95
545°	11·16	2,032°	0·0

Since copper is used for steam pipes, fireboxes, &c., where it has to resist straining action when heated, the reduction of

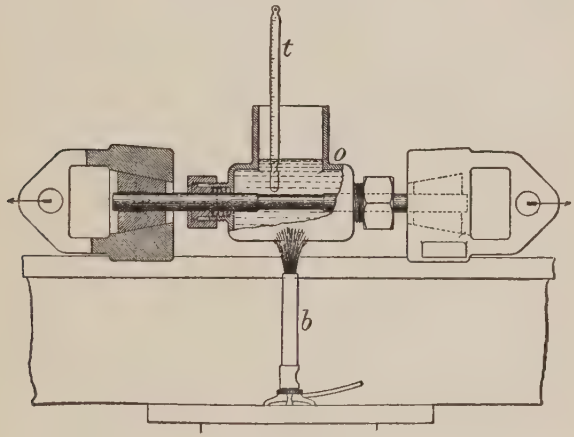


FIG. 177.

strength by rise of temperature is an important consideration. The following are some results obtained by Professor Martens:

Temperature, Fahr.	Stress at yield point, tons per sq. in. p_S	Tensile strength, tons per sq. in. p_B	Extension per cent. in 3·54 ins. 100λ	Contraction of area, per cent.	$\frac{p_S}{p_B}$
Atmospheric	17·1	18·5	14·9	55	0·92
212°	16·2	17·5	8·2	56	0·92
392°	13·8	15·4	7·8	52	0·89
572°	9·5	13·2	10·7	43	0·69
752°	5·1	9·1	6·7	10	0·56

240. *Effect of Temperature on the Strength of the Alloys.*—In 1877 experiments were made under the direction of

the Admiralty, at Portsmouth Dockyard, on the effect of temperature on bronzes. The test bars were heated in an oil bath, and then quickly removed to the testing-machine and broken, the operation lasting only about a minute. This is not quite so satisfactory as breaking specimens in an oil bath. All varieties of gun-metal in these experiments show a slow decrease of tenacity up to a certain temperature, at which the tenacity suddenly falls to about half its previous value

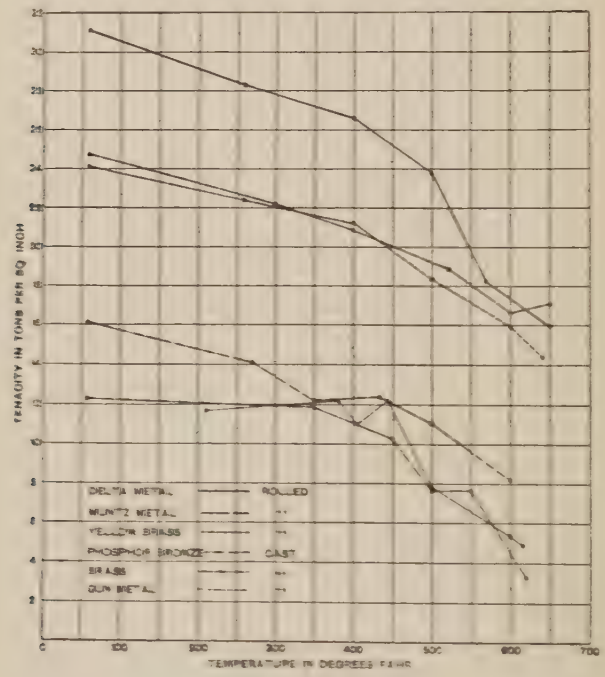


FIG. 178.

and the ductility is almost lost. The temperature at which the change occurred was about 370° F. in series I. and 250° in series II. Phosphor bronze was less affected. Rolled Muntz metal and copper did not suffer serious loss of strength below 450°.

Experiments on Strength of Alloys at Different Temperatures by the Author.—The results of a series of tests on alloys were communicated to the British Association in 1889.[1] In

[1] 'The Strength of Alloys at Different Temperatures.' Unwin, *Report of Brit. Assoc.*, 1899.

these experiments the bars to be tested were fixed in an oil bath *o* (fig. 177), heated by a gas jet *b*, the temperature being taken by a mercurial thermometer *t*. The middle part of the test bar for a length of 2 in. was turned down to a diameter of $\frac{1}{4}$ in. or $\frac{5}{16}$ in.

Rolled bars of yellow brass, Muntz metal, and delta metal were tried, and the results on these are quite regular. Some bars of cast brass also gave very fairly regular results. The bars of gun-metal gave results of less regularity. This is due, in part at all events, to the fact that some of the bars cast first proved unsound, and new bars had to be cast to replace them.

The results are plotted in a diagram (fig. 178), and show that in all cases the decrease of strength follows a regular law without any such sudden loss of strength as was shown

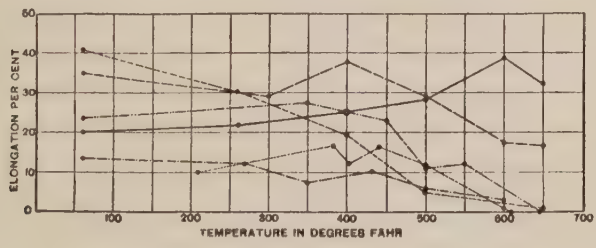


FIG. 179.

in the Admiralty experiments. Even at temperatures of 600° to 650° all the bars had still a not inconsiderable tenacity.

The ultimate elongation of the bars in a 2-in. gauge-length was measured, and is given in the table and fig. 179. There is a peculiarity in the influence of temperature on the ductility of the bars. In most cases the ultimate elongation diminishes with increase of temperature. With Muntz metal the decrease is regular, and there is still considerable elongation before fracture at a temperature of 650°. With yellow brass (rolled) the decrease is more rapid, and there is very little elongation before fracture at temperatures above 500°. Cast brass behaves in the same way. The elongations of the gun-metal bars were very irregular, and at temperatures of 600° and upwards the elongation was extremely small.

On the other hand, in the case of the delta metal bars the elongation increased regularly with the increase of temperature.

The contraction of area was also measured. This follows generally the same law as the elongation at fracture, but the contractions of area are more irregular than the elongations.

TESTING OF ALLOYS AT DIFFERENT TEMPERATURES (UNWIN)

Laboratory No.	Diameter in inches	Section in sq. in.	Temperature, Fahr.	Tenacity, in tons per sq. in.	Elongation in 2 ins., per cent.	Contraction of section, per cent.
			Yellow Brass			
938	·308	·07451	atmospheric	24·09	41·0	61·0
941	·309	·07499	258°	22·44	30·5	28·0
939	·307	·07402	400°	21·23	19·0	10·0
940	·312	·07645	500°	18·33	5·0	very little
942	·308	·07402	602°	15·86	2·5	,, ,,
943	·309	·07499	640°	14·49	1·0	,, ,,
			Delta Metal (Rolled)			
945	·249	·04870	atmospheric	31·16	20·0	55·0
949	·243	·04638	260°	28·30	22·0	47·0
946	·249	·04870	400°	26·58	25·0	53·0
944	·249	·04870	500°	23·83	27·9	59·0
947	·245	·04714	570°	19·32	38·5	60·0
948	·240	·04524	650°abt.	16·04	33·0	48·0
			Muntz Metal			
950	·302	·07163	atmospheric	24·68	35·0	59·6
951	·309	·07499	300°	22·83	28·5	41·2
952	·310	·07548	400°	20·84	37·5	55·1
953	·311	·07596	500°	18·81	28·5	38·4
954	·306	·07354	600°	16·69	17·0	19·2
955	·310	·07548	650°	17·15	16·0	very little
			Gun Metal			
977	·376	·11104	210°	11·66	10·0	15·8
980	·376	·11104	380°	12·26	17·0	18·2
979	·376	·11104	406°	11·06	12·5	12·8
957	·309	·07499	440°	12·30	16·5	7·6
981	·376	·11104	500°	7·84	13·0	14·8
978	·376	·11104	600°	5·22	1·5	2·1
982	·376	·11104	600°	7·84	—	very little
960	·311	·07596	615°	4·82	—	,, ,,
			Cast Brass			
989	·376	·11104	atmospheric	12·45	24·0	16·4
981	·376	·11104	350°	11·83	27·5	23·4
992	·376	·11104	450°	10·40	23·0	22·5
990	·375	·11045	500°	7·69	11·5	16·2
993	·376	·11104	550°	7·68	13·5	17·8
994	·376	·11104	645°	3·23	—	very little
			Phosphor-bronze			
995	·312	·07645	atmospheric	16·06	13·5	10·0
996	·312	,,	270°	14·16	12·5	12·4
997	·312	,,	350°	12·26	7·5	10·0
998	·312	,,	430°	12·41	10·5	8·7
999	·312	,,	500°	11·10	6·0	6·3
1,000	·312	,,	600°	8·17	3·5	2·5

TESTING OF ALLOYS AT DIFFERENT TEMPERATURES—*continued*

Laboratory No.	Diameter in inches	Section in sq. in.	Temperature, Fahr.	Tenacity, in tons per sq. in.	Elongation in 2 ins., per cent.	Contraction of section, per cent.
			Copper (*Rolled*)			
1,030	·313	·0769	atmospheric	17·84	10·0	49·2
1,036	·313	·0769	210°	17·41	9·0	49·7
1,031	·314	·0774	300°	16·43	8·0	49·5
1,032	·313	·0769	410°	15·95	9·0	50·6
1,033	·313	·0769	500°	15·09	7·0	37·7
1,034	·314	·0774	600°	14·30	4·0	22·2
1,035	·313	·0769	600°	14·18	5·0	17·4
1,039	·313	·0769	640°	13·70	4·5	17·1
			Delta Metal (*Cast*)			
1,022	·312	·0764	atmospheric	20·15	4·5	6·3
1,027	„	„	„	18·25	4·0	7·0
1,023	„	„	310°	23·36	7·0	11·8
1,028	„	„	410°	22·48	9·0	13·0
1,025	„	„	506°	19·68	16·0	22·3
1,026	„	„	590°	16·00	4·0	9·4
1,029	„	„	635°	12·70	45·0	45·7
			Aluminium Bronze (10 *per cent.*)			
1,058	·262	·0539	350°	38·50	26·3	28·2
1,057	·257	·0519	500°	37·87	27·5	28·0

241. *Influence of Mechanical Action on the Strength of Bronze.*[1]—The specimens of bronze were 3 inches in length and 0·077 sq. in. section. They were subjected to the following preparation:

I. Metal as cast.

II. Metal subjected to a continued tensile stress of 49 cwt., which produced an elongation of 16·7 per cent.

III. Metal subjected to a compressive stress of 15·87 tons per sq. in. for ten minutes before testing.

IV. Metal elongated 20 per cent. by rolling.

Experiment II. shows, in Major-General Uchatius's opinion, that homogeneous bronze is susceptible of having its elasticity greatly increased by mere stretching without compression. A bronze with an elastic limit of 15·75 tons and a ductility such that it elongates 37 per cent. was previously unknown.

[1] Uchatius, *Proc. Inst. Civil Eng.*, xlix. 284.

Bar	Breaking stress in tons, per sq. in.	Elastic limit in tons per sq. in.	Elongation per cent.		Density
			Ultimate	At elastic limit	
I.	19·4	2·54	50·0	·040	8·863
II.	21·1	15·75	37·3	·478	8·856
III.	24·8	3·17	29·5	·058	8·957
IV.	32·2	10·79	2·1	·170	8·975

242. *Strength of Copper Wire.*—Copper wire is important from its large use in telegraphic and telephonic circuits and for cables and trolley wires.

The following table contains mean results of tests of annealed, half-hard, and hard-drawn copper wire received from five manufacturers. The tests were made at Zurich by Prof. Schüle and E. Brunner. They show strikingly how the tenacity increases and the ductility diminishes as the wire is drawn down to smaller sizes.

STRENGTH AND ELONGATION OF COPPER WIRE

Diameter of wire, ins. d	Tenacity, tons per sq. in. T	Strength of wire in lbs. P	Elongation per cent.
	Annealed		
·32	14·7	2645	39·8
·24	15·0	1518	38·4
·16	15·7	707	35·9
·08	16·1	181	35·7
·04	15·9	46	33·8
	Half Hard		
·32	19·3	3473	11·2
·24	20·0	2024	7·1
·16	21·7	977	4·7
·08	23·9	268	1·7
·04	22·2	65	1·4
	Hard Drawn		
·32	24·0	4325	2·9
·24	24·8	2510	2·5
·16	26·6	1198	2·0
·08	28·3	317	1·2
·04	25·7	80	0·9

These results are represented approximately by the equations:

Annealed . . . . $P = 262d + 25000d^2$
Half Hard . . . . $P = 850d + 31400d^2$
Hard Drawn . . . . $P = 788d + 39800d^2$

For English hard drawn telegraphic copper wire, not over 0·25 inch in diameter, the strength of the wire in pounds is given by the equation:

$$\begin{aligned} P &= 500d + 44000d^2 \text{ lbs.} \\ &= 3{\cdot}955\sqrt{w} + 2{\cdot}753w \text{ lbs.,} \end{aligned}$$

where d is the diameter in inches and w the weight in pounds per mile.

Diameter ins.	Weight in lbs. per mile	Strength in lbs.	Elongation, per cent. in 8 ins.
·2237	800	2314	—
·1937	600	1748	1·7
·1582	400	1180	1·4
·1370	300	884	1·1
·1119	200	606	1·0
·0969	150	461	—
·0791	100	315	0·8
·0662	70	225	—

The following are results of some tests of various wires:

No. of specimen	Description	Diameter	Sq. in. area	Tenacity, tons per sq. in.	Extension in 8 ins., per cent	—
—	Brass wire . .	·1929	·0290	25·23	25·5	Unwin
112	Black cast-steel rod	·191	·0286	62·04	4·12	,,
113	,, ,, .	·191	·0286	62·44	5·76	,,
124	Gilding metal (no tin)	·249	·0487	20·17	6·25	,,
125	,, ,, .	·249	·0487	20·62	8·7	,,
127	Soft German silver .	·267	·0560	29·89	47·0	,,
128	,, ,, . .	·267	·0560	29·10	47·7	,,
	Silicium bronze .	·08	—	27·5	1·5	Preece
	,, ,, . .	·036	—	50·0	nil	,,
	Delta metal . .	·115	—	58·2	2·1[1]	Fairfield Co
	,, ,, annealed	·115	—	38·7	27·0[1]	

[1] In 6 inches.

CHAPTER XVI

EXPERIMENTS ON REPETITION OF STRESS ENDURANCE TESTS

243. In 1871 was published a Report by Herr A. Wöhler on the endurance of bars subjected to repetitions of stress.[1] It occurred to Herr Wöhler that most structures, especially such machine parts as railway axles, springs, and piston-rods, are subjected to a continual variation of stress, and that direct experiment, in conditions imitating those which occur in practice, might afford useful information as to the limits of stress permissible in such cases. Herr Wöhler carried out a series of experiments, extending over a period of twelve years, and undoubtedly the results are of great importance.

Wöhler's Machine for Repetitions of Torsional Stress (fig. 180).—The test bar is a simple cylindrical bar with enlarged ends. An oscillating lever c, driven by a connecting-rod, is attached by a link s to the lever h' on the back end of the test bar. The stroke of the lever c can be adjusted by moving the connecting-rod pin in a slot in the lever. At the upper end of the link s there are nuts, which come in contact with knife-edges on the lever h', and which give a further means of adjusting the stroke of the lever h'. To ensure the bar from being strained beyond the exact stress intended, the opposite or front end of the test bar is fixed in the double-lever h. This lever presses on the short ends of the levers g, g', the other ends of which rest on the bearing screws k, k, and which are held down by the long springs f, f. If the torsion given by the lever h' is in excess of a fixed amount, the lever h lifts either the lever g or g' against the spring. By adjusting the springs, the exact stress at which the levers

[1] *Ueber die Festigkeitsversuche mit Eisen und Stahl.* Angestellt von A. Wöhler, Ober-Maschinenmeister an der Königl. Nieder-Schlesisch-Märkischen Eisenbahn. Berlin. A good account of Wöhler's results is given in *Engineering*, vol. xi. No other tolerably complete account has appeared in English.

g or g' lift can be arranged. If the test bar is to be twisted in one direction, only one of the levers g or g' is required. If the stroke of the lever h' is large enough it twists the bar

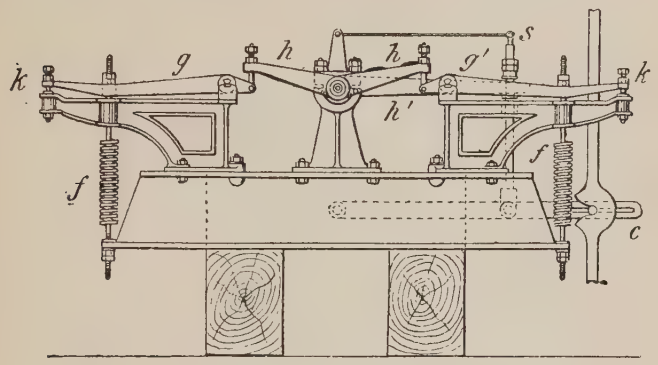


Fig. 180

alternately in opposite directions, and then both levers, g and g', are used to limit the stresses. When working in adjustment, the stroke of h' is sufficient to just lift one or both the levers g or g' at each stroke.

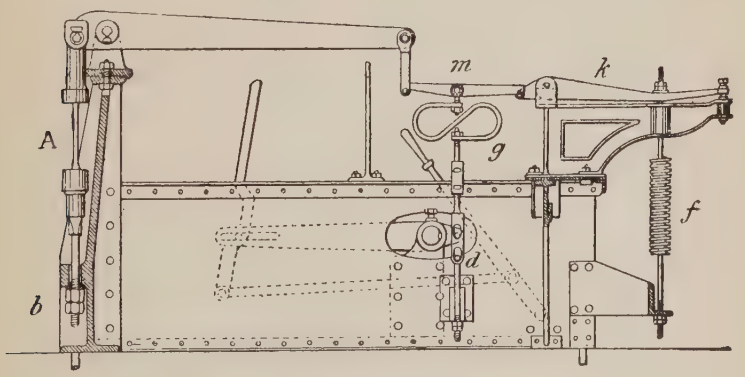


Fig. 181

Wöhler's Machine for Repeated Tensions (fig. 181).—This consists of a wrought-iron bed-plate, at the left-hand end of which is a cast-iron standard, supporting the knife-edge of the principal lever h. The test bar A is held in a shackle attached to the lever; the other shackle is attached to an adjusting-screw b. The long arm of the lever is connected

by a link to the equal-armed beam m. The centre of this beam is pulled down by a lever worked by a connecting-rod, a bent spring g being interposed to prevent shock. The other end of m rests on the short arm of the lever k, which has a bearing-screw and long spring f, as in the torsion machine. If the pull on m exceeds a certain value the lever k lifts, and by adjusting the spring f the tension can be regulated as desired. To facilitate the adjustment, the rod d, by which the pull is applied to the beam m, is in two parts, connected by a long coupling nut with right and left hand screws. The rod d is continued down through a bracket,

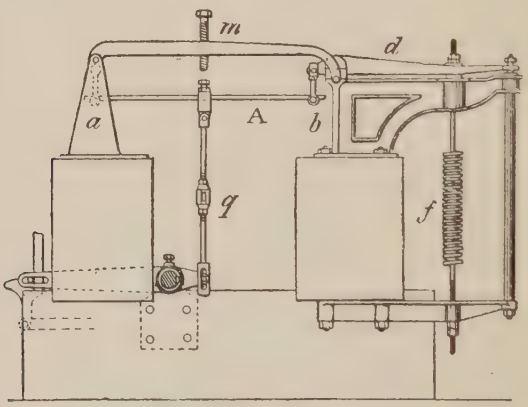


FIG. 182

and a nut under this bracket serves to limit the extent to which the test bar is relieved of stress.

In adjusting the machine to give a range of tension between a fixed lower and fixed upper limit, the spring f is first adjusted to the minimum stress. The nut on the end of d can then be adjusted, so that when d rises it just keeps the lever k lifted. Then the spring f is adjusted for the maximum stress, and the machine is ready for use. As made by Wöhler the machine had four sets of levers, so that four bars could be tested simultaneously.

Wöhler's Machine for Repetition of Bending Stresses.—For applying repeated bending stresses to bars, the stress ranging between a fixed lower and upper limit, Wöhler employed the machine shown in fig. 182. The test bar A rests on knife-edges carried by pairs of links. At a the links are suspended

from a fixed bracket. At b they hang from the short arm of the lever d. This lever has a bearing-screw at its longer end, and it is held down by a spring f. The bar is bent by the rod q, furnished with an adjusting coupling, and moved up and down by a lever and connecting-rod. When the bar is not to be entirely released from stress, but to be strained between a fixed upper and lower limit of stress, the screw m is used. As the bar unbends it comes in contact with m at some fixed amount of deflection. To adjust the screw m, the spring f is set to the desired minimum tension, and the screw m is then adjusted till it just lifts the lever d. Then the spring f is set to the maximum tension, and the machine is ready for use.

Wöhler's Machine for Repeated Bending in Opposite Directions.—For repeated bendings in opposite directions Wöhler used the very simple machine shown in fig. 183. It consists

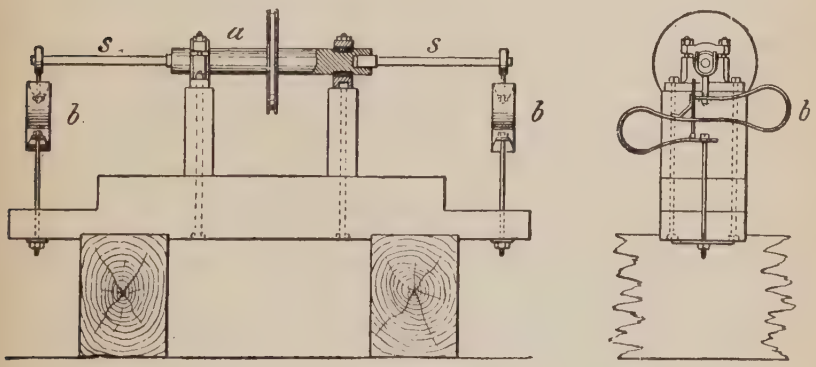


FIG. 183

of a wooden frame carrying in bearings the axle a, which is rotated by a belt. In the ends of a are conical recesses, into which two test bars can be fixed by driving. After being fixed, the test bars are turned in the lathe so as to run truly. At the end of the test bars are fixed spring balances, which can be adjusted to any required stress. As the bar rotates every fibre is subjected to bending alternately in opposite directions, precisely as is the case with journals of railway axles.

It is not distinctly stated, but it appears that in Wöhler's tests the changes of stress were at less than 100 per minute.

244. *Osborne Reynolds Throw Testing-machine for Alternating Stresses.*—In this machine an alternate axial thrust and tension of nearly equal amount is obtained. A rotating crank C (fig. 184) gives periodic harmonic motion to a heavy mass B through a connecting-rod. The test bar S forms part of the connection between the reciprocating mass and the cross-head A. It is strained by the alternating inertia forces of the mass B. In the original machine a single crank operated two equal masses in the same vertical plane, to one of which, moving vertically, the test bar was attached, and the other, moving horizontally, was used to keep the kinetic energy of the system constant. A larger and improved machine has been constructed at the National Physical Laboratory. Four cranks operate four reciprocating masses, which act on four test bars.

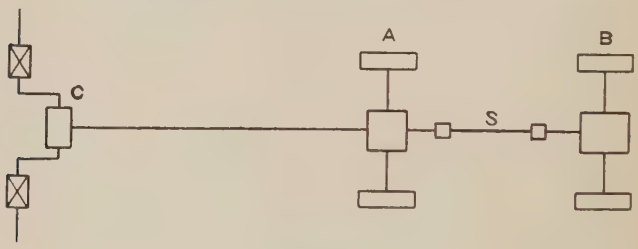


FIG. 184.

The machine is then perfectly balanced. The masses reciprocate horizontally.

There are therefore two independently balanced systems on the same crank shaft, each having cranks at 180° apart. The cranks of one system are at right angles to those of the other, so that the kinetic energy of the moving parts is approximately constant, and the speed constant. The main crank pins are 3 ins. in diameter, 4 ins. long, and the crank is 2 ins. radius. The main crossheads have cast-iron slipper blocks sliding on cast-iron guides. Secondary crossheads, also guided, form the reciprocating masses which strain the test bars. These have cast-iron plates bolted symmetrically on each side of the centre, which serve to vary the reciprocating masses. The test bars consist of turned bars 5 ins. long and $\frac{3}{4}$ inch diameter, reduced in the middle to $\frac{1}{4}$ inch diameter for a length of $\frac{1}{2}$ inch, the ends being screwed to fit the holders. If a test bar breaks a clutch comes into action

which keeps the secondary crosshead moving, and an electrical signal is given so that time and counter readings may be taken. The machine is driven by an electric motor with speed regulator, so that speeds of 500 to 2000 r.p.m. can be obtained. Experiment showed that the friction of the secondary crossheads is very small near the dead point, when the stress on the test bars is a maximum. Hence the only force acting on a test bar is the inertia of the reciprocating mass of the secondary crosshead. As the crank radius is one-sixth of the connecting-rod length, the motion is not simple harmonic. Let w be the reciprocating mass in lbs.; r the crank radius; l the connecting-rod length; ω the angular velocity of the crank. Then the forces acting on the test bar are—

$$\text{Tension} \quad . \quad . \quad . \quad \frac{w}{g}\,\omega^2 r\,(1+\frac{r}{l}) \text{ lbs.}$$

$$\text{Compression} \quad . \quad . \quad \frac{w}{g}\,\omega^2 r\,(1-\frac{r}{l}) \text{ lbs.}$$

With the proportions chosen the maximum tension is 1·4 times the maximum thrust.

245. *Results of Wöhler's Endurance Tests.*—The following tables contain all Wöhler's more important results. Table I. gives some ordinary statical tests of the materials used in the subsequent endurance tests. The elongation was probably measured in 8 inches, but the length is not given.

TABLE I. STATICAL TENSILE STRENGTH OF THE MATERIALS EXPERIMENTED ON BY WÖHLER

No. of bar	Material	Tenacity, in tons per sq. in.	Elongation, per cent.
	WROUGHT IRON:		
1	Phœnix Co.'s axle	21·1	17·8
2	„ „	21·5	21·8
3	Bar iron from Königshütte . .	29·2	7·0
4	„ „	24·4	20·8
5	Rivet iron (Berlin, Borsig) . .	33·0	22·0
6	„ „	34·0	23·6
7	Boiler stay iron (Borsig) . . .	29·6	17·0
8	„ „	24·4	19·0
	HOMOGENEOUS IRON:		
9	Pearson, Coleman & Co. . . .	27·5	24·6
10	„ „	27·7	16·2
11	„ „	29·2	21·7

TABLE I.—*continued.*

No. of bar	Material	Tenacity, in tons per sq. in.	Elongation, per cent.
	CAST-STEEL AXLES AND BARS:		
12	Krupp, steel axles	49·0	12·1
13	„ „	49·7	18·6
14	„ „	49·7	11·7
15	„ „	41·8	23·7
16	„ „	41·8	17·4
17	Bochum Company, steel axles . .	42·0	18·3
18	„ „ . .	42·5	19·0
19	Borsig, steel axles	39·4	21·7
20	„ „	37·3	22·3
21	Vickers, Sons, & Co., steel axles .	29·2	19·5
22	„ „ „ . .	26·3	15·8
23	Werner, hardened-steel axle . .	52·3	1·1
24	„ „ „ . .	60·2	2·2
25	„ same axle annealed . .	48·7	2·7
26	Krupp, cast-steel rails . . .	47·8	15·8
27	„ „ . . .	48·7	15·4
28	Firth & Sons, tool steel . . .	55·0	9·1
	CAST-STEEL PLATES:		
29	Krupp, ⊥ direction of rolling . .	33·9	12·2
30	„ „ „ . .	36·3	10·8
31	„ ‖ direction of rolling . .	32·0	10·2
32	„ „ „ . .	36·3	9·5
33	„ „ „ . .	37·7	22·0
34	Borsig	33·0	22·3

TABLE II. EXPERIMENTS ON BARS SUBJECTED TO REPEATED TWISTINGS (WÖHLER)

No. of bar	Material	Stress applied (at surface of bar) in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions before fracture
		Maximum	Minimum		
	I. *Torsion in one direction only*				
1	Krupp's axle steel	22·9	0	22·9	198,600 [1]
2		21·5	0	21·5	373,800
3		20·1	0	20·1	334,750
4		19·1	0	19·1	879,700
5		18·1	0	18·1	[23,850,000] [2]
	II. *Equal alternate torsions in opposite directions*				
6	Krupp's axle steel	+13·4	−13·4	26·8	187,500 [3]
7		+12·4	−12·4	24·8	1,007,550
8		+11·5	−11·5	23·0	859,700
9		+10·5	−10·5	21·0	[19,100,000] [2]

[1] Had previously suffered 286,000 repetitions of stress of 21·5 tons per sq. in.

[2] Not broken.

[3] Had previously suffered 1,070,000 repetitions of a stress of from 9·5 to 12·4 tons per sq. in.

Only a few endurance tests with the torsion machine are given. These consist of some experiments with Krupp's axle steel, some twisted in one direction only and others in opposite directions alternately.

TABLE III. WÖHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPEATED TENSIONS BETWEEN DEFINITE LIMITS

No. of bar	Form of bar	Material	Stress applied in tons per sq. in.		Range of stress in tons per sq. in.	Number of repetitions before fracture
			Maximum	Minimum		
1	A	Iron axle, Phœnix Company	22·92	0	22·92	800
2	A		21·01	0	21·01	106,910
3	A		19·10	0	19·10	340,853
4	A		17·19	0	17·19	409,481
5	A		17·19	0	17·19	480,852
6	A		15·28	0	15·28	10,141,645
7	A		+21·01	+ 9·55	11·46	2,373,424
8	A		+21·01	+11·46	9·55	[4,000,000] [1]
9	B		17·10	0	17·10	37,828
10	A	Krupp's axle steel	38·20	0	38·20	18,741
11	A		33·40	0	33·40	46,286
12	A		28·65	0	28·65	170,170
13	A		26·14	0	26·14	123,770
14	A		23·87	0	23·87	473,766
15	A		22·92	0	22·92	[13,600,000] [1]
16	A		21·95	0	21·95	[13,200,000] [1]
17	A		+38·20	+23·87	14·33	[1,801,000] [1]
18	A		38·20	19·10	19·10	[12,100,000] [1]
19	A		38·20	16·70	21·50	[12,000,000] [1]
20	B	Krupp's axle steel	23·89	0	23·89	23,546
21	B		21·97	0	21·97	35,486
22	B		20·08	0	20·08	65,658
23	B		19·10	0	19·10	75,343
24	B		17·18	0	17·18	208,883
25	B		15·29	0	15·29	274,970
26	B		14·34	0	14·34	[1,100,000] [1]
27	A	Cast iron from locomotive cylinder	7·62	0	7·62	3,140
28	A		6·69	0	6·69	4,000
29	A		6·22	0	6·22	10,342
30	A		5·73	0	5·73	45,028
31	A		5·26	0	5·26	78,682
32	A		5·03	0	5·03	27,885
33	A		5·03	0	5·03	35,599
34	A		4·78	0	4·78	208,439
35	A		4·78	0	4·78	[7,200,000] [1]
36	A		4·78	0	4·78	[7,600,000] [1]

[1] Not broken.

For any given straining a certain number of repetitions of load produce fracture, the smaller the greater the range of stress. But below a certain range of stress a practically unlimited number of repetitions of load is required to cause fracture. Roughly speaking, the stress, for which an unlimited number of repetitions is required to cause fracture, is only half as great when the bar is alternately strained in opposite directions as when it is strained in one direction. A bar twisted in one direction only will stand 24 million repetitions of a stress of 18 tons per sq. in., a much larger stress than would ordinarily be considered safe.

Table III. gives Wöhler's results on the endurance of bars subjected to repetitions of tensile stress, the stress in some cases varying from zero to a maximum limit, in others from a minimum to a maximum value. Two forms of bars were tried. The bars marked A had well-rounded corners at the point where the small middle part joined the enlarged end. Those marked B had square corners. It may be noted at once that for any given stress the bars B broke with far fewer repetitions of stress than the bars A. Thus, bar 5 of form A stood 480,000 repetitions of a stress of 17·19 tons per sq. in., while bar 9 of form B stood only 37,000 repetitions of a stress of 17·10 tons per sq. in. Bar 16 of form A was not broken with 13,000,000 repetitions of a stress of 22 tons per sq. in., while bar 21 of form B broke with 35,000 repetitions of this stress.

The next point in Table III. is that *the range of variation of stress*, not the greatest stress, determines the number of repetitions before fracture. Thus, bars 7 and 8 endured nearly as many repetitions as bar 6, though in the former case the maximum stress was 21 tons and in the latter 15. But the load was not entirely taken off bars 7 and 8, and the range of stress was only $9\frac{1}{2}$ and $11\frac{1}{2}$ tons. Again, bar 18 is not broken with 12,000,000 repetitions of a stress of 38 tons per sq. in., the minimum load being 19 tons per sq. in.; but bar 10 broke with 19,000 repetitions of a stress of 38 tons, the minimum stress being zero.

This table contains some results on cast iron which are interesting. Although this material is somewhat more irregular in quality than wrought iron or steel, it appears to behave in the same general way.

In Table IV. are given the results on the endurance of bars subjected to bending. These exactly confirm those

obtained with torsion and simple tension. Further, as bending tests are made more easily than other tests, and the deflections are large and easily determined, these

TABLE IV. WÖHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPETITIONS OF TRANSVERSE STRESS (REPEATED BENDINGS) BETWEEN DEFINITE LIMITS

No. of bar	Bars marked H were hardened	Material	Stresses applied in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions of load before fracture
			Maximum	Minimum		
1	—	Iron for axles, made by Phœnix Company	26·25	0	26·25	169,750
2	—		23·87	0	23·87	420,000
3	—		21·50	0	21·50	481,950
4	—		19·10	0	19·10	1,320,000
5	—		17·18	0	17·18	4,035,400
6	—		15·28	0	15·28	[3,420,000] [1]
7	—		14·33	0	14·33	[48,200,000] [1]
8	—	Homogeneous iron	38·20	19·10	19·10	475,500
9	—		33·41	14·31	19·10	1,234,600
10	—		19·10	0	19·10	[34,500,000] [1]
11	—	Krupp's cast-steel axles	26·25	0	26·25	1,762,300
12	—		25·07	0	25·07	1,031,200
13	—		24·83	0	24·83	1,477,400
14	—		23·87	0	23·87	5,234,200
15	—		23·87	0	23·87	[40,600,000] [1]
16	—	Bochum Company's steel axles	33·41	0	33·41	104,300
17	—		28·65	0	28·65	317,275
18	—		26·25	0	26·25	612,500
19	—		23·87	0	23·87	729,400
20	—		23·87	0	23·87	1,499,600
21	—		21·50	0	21·50	[43,000,000] [1]
22	—	Krupp's steel plates	25·07	0	25.07	175,300 [2]
23	—		23·15	0	23·15	387,700 [2]
24	—		23·87	0	23·87	[4,100,000] [1] [2]
25	—		22·93	0	22·93	271,800 [2]
26	—		28·65	0	28·65	420,100 [3]
27	—		26·10	0	26·10	[3,600,000] [1] [3]
28	H	Krupp's spring steel	52·50	0	52·50	54,600
29	H		47·75	0	47·75	76,300
30	H		42·95	0	42·95	200,100
31	H		38·20	0	38·20	339,150
32	H		35·85	0	35·85	330,750
33	H		35·85	0	35·85	389,200
34	H		33·40	0	33·40	293,300
35	H		33·40	0	33·40	455,700
36	H		33·40	0	33·40	268,900
37	H		28·65	0	28·65	[36,500,000] [1]

[1] Not broken. [2] Across direction of rolling. [3] In direction of rolling.

TABLE IV.—*continued.*

No. of bar	Bars marked H were hardened	Material	Stresses applied in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions of load before fracture
			Maximum	Minimum		
38	—	Krupp's spring steel	47·75	0	47·75	39,950
39	—		42·95	0	42·95	72,450
40	—		38·20	0	38·20	132,650
41	—		38·20	0	38·20	117,000
42	—		33·40	0	33·40	197,400
43	—		28·65	0	28·65	468,200
44	—		23·87	0	23·87	[40,600,000] [1]
45	—		21·50	0	21·50	[32,942,000] [1]
46	H	Krupp's spring steel	57·30	14·33	42·97	22,900
47	H		19·10	38·20	35,600	
48	H		23·87	33·43	86,000	
49	H		28·65	28·65	191,100	
50	H		33·42	23·88	50,100	
51	H		33·42	23·88	251,400	
52	H		38·20	19·10	[35,600,000] [1]	
53	H		42·95	14·35	33,478,700	
54	—	Krupp's spring steel	47·75	7·92	39·83	62,000
55	—		15·92	31·83	149,800	
56	—		23·87	23·88	400,050	
57	—		27·83	19·92	376,700	
58	—		31·52	16·23	[19,673,300] [1]	
59	—		42·95	9·55	33·40	81,200
60	—		14·33	28·62	156,200	
61	—		19·10	23·85	225,300	
62	—		23·87	19·08	1,238,900	
63	—		23·87	19·08	300,900	
64	—		28·65	14·30	[33,600,000] [1]	
65	—		38·20	4·77	33·43	99,700
66	—		9·55	28·65	176,300	
67	—		14·33	23·87	619,600	
68	—		14·33	23·87	2,135,670	
69	—		19·10	19·10	[35,800,000] [1]	
70	—		19·10	19·10	[38,000,000] [1]	
71	—		26·75	11·45	[36,000,000] [1]	
72	—		33·41	4·77	28·64	286,100
73	—		9·55	23·86	701,800	
74	—		11·94	21·47	[36,600,000] [1]	
75	—		14·33	19·08	[31,150,000] [1]	
76	H	Bochum Company's spring steel	52·50	0	52·50	45,850
77	H		47·75	0	47·75	108,850
78	H		42·95	0	42·95	93,800
79	H		38·20	0	38·20	148,400
80	H	Mayr's spring steel	47·75	0	47·75	39,860
81	—		33·42	0	33·42	212,700
82	—		31·04	0	31·04	360,100
83	—		28·65	0	28·65	[30,500,000] [1]
84	—		23·87	0	23·87	[26,260,000] [1]

[1] Not broken.

TABLE IV.—*continued.*

No. of bar	Bars marked H were hardened	Material	Stresses applied in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions of load before fracture
			Maximum	Minimum		
85	H	Seebohm's spring steel	62·10	0	62·10	28,350
86	H		57·30	0	57·30	45,500
87	H		52·50	0	52·50	46.550
88	H		47·75	0	47·75	141,750
89	H		45·35	0	45·35	190,050
90	—	Seebohm's spring steel	42·95	0	42·95	80,850
91	—		38·30	0	38·30	154,000
92	—		33·42	0	33·42	210,000
93	—		28·65	0	28·65	471,800
94	—		26·25	0	26·25	538,850
95	—		23·87	0	23·87	1,165,500

experiments are numerous and very regular. The stress given in the tables is that of the extreme fibres, calculated from the load, by the usual formula $f = M / z$; and of course this stress, for all cases in which the elastic limit is exceeded, is greater than the real stress due to the load. Whatever error there is in the calculated stress given in Wöhler's tables is in excess, and the bars broke, in fact, with smaller stresses than those calculated and recorded in the tables. Bending experiments are not less trustworthy than tension experiments, and for stresses considerably less than the statical breaking weight probably the error in the calculated stress is not a large one.

Lastly, Table V. gives the results of experiments on rotating bars subjected to bending. As the bar turns round, while bent in a fixed direction by the spring, every fibre is alternately in compression and tension, and these are the only experiments of Wöhler in which alternate opposite stresses of tension and compression were obtained. The torsional experiments agree with the bending experiments as to the effect of stresses in opposite directions.

Wöhler tried three forms of bars in this research. Two of these had square corners at the enlarged end. These two forms were relatively much weaker than the bars of the third form with rounded corners, and only the results of these latter are given in the following table:—

TABLE V. WÖHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPETITIONS OF TRANSVERSE STRESS (ROTATING BARS) BETWEEN EQUAL AND OPPOSITE LIMITS OF STRESS

No. of bar	Material	Stress applied in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions before fracture
		Maximum	Minimum		
1	Iron for axles, Phœnix Company	+ 15·3	− 15·3	30·6	56,430
2		14·3	14·3	28·6	99,000
3		13·4	13·4	26·8	183,145
4		12·4	12·4	24·8	479,490
5		11·5	11·5	23·0	909,840
6		10·5	10·5	21·0	3,632,588
7		9·6	9·6	19·2	4,917,992
8		8·6	8·6	17·2	19,186,791
9		7·6	7·6	15·2	[132,250,000] [1]
24	Homogeneous iron	+ 23·9	− 23·9	47·8	2,375
25		22·9	22·9	45·8	4,986
26		21·9	21·9	43·8	11,636
27		18·2	18·2	36·4	31,586
28		16·3	16·3	32·6	94,311
29		14·3	14·3	28·6	161,262
30		13·4	13·4	26·8	464,786
31		12·4	12·4	24·8	636,500
32		11·5	11·5	23·0	3,930,150
33	Krupp's cast-steel axles	+ 20·1	− 20·1	40·2	55,100
34		17·2	17·2	34·4	127,775
35		16·3	16·3	32·6	797,525
36		15·3	15·3	30·6	642,675
37		15·3	15·3	30·6	1,665,580
38		15·3	15·3	30·6	3,114,160
39		14·3	14·3	28·6	4,163,375
40		14·3	14·3	28·6	45,050,640
46	Cast-steel axles, Bochum & Co.	+ 17·2	− 17·2	34·4	127,775
47		16·3	16·3	32·6	342,850
48		15·3	15·3	30·6	627,000
49		15·3	15·3	30·6	20,467,780
50		14·3	14·3	28·6	2,845,250
51		14·3	14·3	28·6	[57,360,000] [1]
52		13·4	13·4	26·8	3,558,700
53		12·4	12·4	24·8	[14,176,171] [1]
54	Borsig's cast steel axles	+ 18·2	− 18·2	36·4	157,700
55		17·2	17·2	34·4	239,875
56		16·3	16·3	32·6	553,850
57		15·3	15·3	30·6	1,373,225
58		14·3	14·3	28·6	1,023,625
63	Vickers & Sons' cast-steel axles	+ 16·3	− 16.3	32·6	51,240
64		15·3	15·3	30·6	72,940
65		14·3	14·3	28·6	205,800
66		13·4	13·4	26·8	278,740
67		12·4	12·4	24·8	564,900
68		11·5	11·5	23·0	3,275,860
69		10·5	10·5	21·0	[8,660,000] [1]

[1] Not broken.

TABLE V.—*continued.*

No. of bar	Material	Stress applied in tons per sq. in.		Range of stress in tons per sq. in.	No. of repetitions before fracture
		Maximum	Minimum		
70	Firth & Sons' tool steel	+ 17·2	− 17·2	34·4	370,975
71		16·3	16·3	32·6	694,450
72		15·3	15·3	30·6	233,700
73		14·3	14·3	28·6	1,528,550
74	Copper	+ 7·64	− 7·64	15·28	30,875
75	,,	7·64	7·64	15·28	67,725
76	,,	6·69	6·69	13·38	480,700
77	,,	6·21	6·21	12·42	663,100
78	,,	5·97	5·97	11·94	798,000
79	,,	5·73	5·73	11·46	2,834,325
80	,,	4·78	4·78	9·56	19,327,460

246. *Wöhler's Conclusions.*—In certain structures the whole load is a permanent, or dead, load. With such cases Wöhler's investigation is not concerned. But in most cases a part or the whole of the load is occasional, or varying. In those cases the engineer has to allow for a practically unlimited number of repetitions of load. Railway axles, for instance, may make 300 million revolutions, involving reversal of stress, before being put out of service. With such conditions of straining action, safety depends, not at all on the maximum stress, but only on the range of variation of stress.

The following table gives the stresses and ranges of stress which Wöhler considers to be the limiting values which, in the materials he experimented on, would only produce fracture after an indefinitely large number of repetitions :

TABLE VI. LIMITS OF STRESS FOR UNLIMITED REPETITION OF LOAD (WÖHLER)

Material	Maximum stress, tons per sq. in.	Minimum stress, tons per sq. in.	Range of stress
A. Bars subjected to simple tension, compression, or bending			
Wrought iron	+ 7·65	− 7·65	15·30
,, ,,	+15·80	0	15·80
,, ,,	+21·00	+11·50	9·50
Cast-steel axles	+13·38	−13·38	26·76
,, ,,	+23·00	0	23·00
,, ,,	+38·20	+16·70	21·50
Untempered cast-steel springs	+23·90	0	23·90
,, ,, ,,	+33·50	+11·50	22·00
,, ,, ,,	+38·30	+19·10	19·20
,, ,, ,,	+43·00	+28·70	14·30
B. Bars subjected to shearing or torsion			
Cast-steel axles	10·50	−10·50	21·00
,, ,,	18·20	0	18·20

247. *Experiments by Spangenberg* entirely support Wöhler's conclusions. If the stresses are plotted as abscissæ, and the number of repetitions causing fracture as ordinates, curves are obtained such as those in fig. 185. These curves cut the axis of abscissæ at the statical breaking stress, and they are

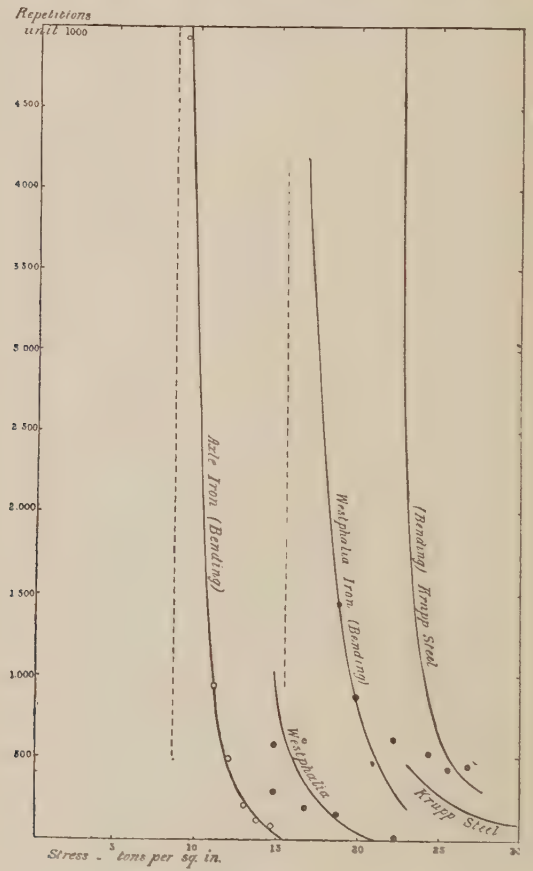


FIG. 185.

asymptotic to a vertical, the abscissa of which is the stress which the bar will carry if repeated an unlimited number of times.

248. *Endurance Tests made by Sir B. Baker.*[1]—Sir B. Baker has given the results of a series of experiments on iron

[1] 'Notes on the Working Stress of Iron and Steel,' *Am. Soc. of Mech. Engineers*, 1886.

and steel made with a machine like that shown in fig. 183. The rotating bars were 1 inch in diameter and the weight was hung at 10 inches from the fixed end. The bars rotated 50 to 60 times a minute. The soft steel was fine rivet steel, with a tenacity of 26·8 to 28·6 tons per sq. in., and an elongation of 28 per cent. in 8 inches. The hard steel was fine drift steel, having a tensile strength of 54 tons per sq. in., and an elongation of 14 per cent. in 8 inches. The iron was best rivet iron, with a tenacity of 25·9 to 27·3 tons per sq. in., and an elongation of 20 per cent. in 8 inches.

TABLE VII. EXPERIMENTS ON THE ENDURANCE OF ROTATING BARS SUBJECTED TO BENDING (SIR B. BAKER)

No.	Material	Maximum stress, tons per sq. in.	Minimum stress, tons per sq. in.	Range of stress, tons per sq. in.	Number of repetitions to cause fracture
1	Soft steel	+16·1	−16·1	32·2	40,510
2	,,	16·1	16·1	32·2	60,200
3	,,	15·2	15·2	30·4	68,400
4	,,	15·2	15·2	30·4	92,070
5	,,	15·2	15·2	30·4	107,415
6	,,	15·2	15·2	30·4	128,650
7	,,	15·2	15·2	30·4	155,295
8	,,	11·6	11·6	23·2	14,876,432
9	Hard steel	+29·9	−29·9	59·8	5,760
10	,,	29·1	29·1	58·2	7,560
11	,,	23·9	23·9	47·8	14,600
12	,,	23·9	23·9	47·8	16,300
13	,,	20·8	20·8	41·6	26,100
14	,,	22·8	22·8	45·6	32,445
15	,,	18·1	18·1	36·2	157,815
16	,,	15·2	15·2	30·4	472,500
17	Best bar iron	+15·2	−15·2	30·4	108,160
18		15·6	15·6	31·2	110,000
19		15·2	15·2	30·4	141,750
20		14·3	14·3	28·6	389,050
21		13·5	13·5	27·0	408,000
22		14·3	14·3	28·6	421,170
23		13·8	13·8	27·6	480,810

The following table gives results of experiments on flat bars, some bent alternately in opposite directions, the others bent one way only. The soft steel had a tensile strength of 31·3 tons per sq. in., and an elongation of 20 per cent. in 8 inches. The iron was best bar iron. The bars were 32 inches long, 1 inch wide, and ½ inch thick. The bars 33 and

36 were not actually broken, but when taken out of the machine were found to have deep flaws.

TABLE VIII. ENDURANCE TESTS. BARS SUBJECTED TO BENDING (SIR B. BAKER)

No.	Material	Stress applied in tons per sq. in.		Range of stress in tons per sq. in.	Number of repetitions before fracture
		Maximum	Minimum		
24	Soft steel	+19·7	−19·7	39·4	12,240
25	,,	19·7	19·7	39·4	12,325
26	,,	19·7	19·7	39·4	12,470
27	,,	18·8	18·8	37·6	18,100
28	,,	18·8	18·8	37·6	18,140
29	,,	16·1	16·1	32·2	72,420
30	,,	15·4	15·4	30·8	147,390
31	,,	15·2	15·2	30·4	262,680
32	,,	12·3	12·3	24·6	1,183,200
33	,,	15·4	0	15·4	[3,145,020]
34	Best bar iron	+15·2	−15·2	30·4	184,875
35	Best bar iron	15·2	15·2	30·4	250,513
36	Best bar iron	15·2	0	15·2	[3,145,020]

249. *Bauschinger's Experiments on Repeated Tensions.*—Table IX. contains a summary of Bauschinger's experiments on the endurance of bars subject to repeated stresses. He constructed a machine in which a bar could be subjected to stresses ranging from 0 to an upper fixed limit in tension. He ascertained both the initial elastic limit and the elastic limit acquired under repeated repetition of stress; the initial breaking strength and the strength after the bar had been broken in the machine.

TABLE IX. ENDURANCE TESTS. BARS SUBJECTED TO TENSION (BAUSCHINGER)

(Stresses in tension varying from 0 to an upper limit)

Material	Elastic limit in tons per sq. in.		Endurance test		Tensile strength in tons per sq. in.	
	Original	Acquired during repetition of loads	Load applied, tons per sq. in.	No. of repetitions before fracture in millions	Original	After breaking by repetition of loads
Wrought-iron plate	6·84	12·3	7·1	5·17	25·2	23·6
	6·84	13·2	9·85	5·19	25·2	24·3
	6·84	14·4	13·1	5·18	25·2	24·5
	6·84	16·4	16·4	2·28	25·2	—

TABLE IX.—*continued*

Material	Elastic limit in tons per sq. in.		Endurance test		Tensile strength in tons per sq. in.	
	Original	Acquired during repetition of loads	Load applied, tons per sq. in.	No. of repetitions before fracture in millions	Original	After breaking by repetition of loads
Mild-steel plate	15·6	19·4	16·0	6·68	28·5	—
	15·6	18·0	16·0	3·55	28·5	—
	15·6	20·0	16·0	[11·03]	28·5	—[1]
	15·6	16·4	16·0	7·35	28·5	—
	15·6	—	19·7	0·67	28·5	—
	15·6	19·1	19·7	1·01	28·5	—
	15·6	19·0	23·0	0·32	28·5	—
	15·6	19·0	23·0	0·76	28·5	—
	15·6	19·9	23·0	0·16	28·5	—
	15·6	16·4	23·0	0·44	28·5	—
	15·6	15·3	23·0	0·62	28·5	—
	15·6	20·0	26·2	0·34	28·5	—
	15·6	16·9	26·2	0·49	28·5	—
	15·6	17·9	26·2	0·07	28·5	—
	15·6	12·3	26·2	0·11	28·5	—
	15·6	11·5	26·2	0·04	28·5	—
Bar iron	11·8	21·4	13·2	9·11	26·6	28·2
	11·8	10·7	16·4	7·40	26·6	—[2]
	11·8	10·8	19·7	0·64	26·6	—
	11·8	10·6	19·7	0·24	26·6	—
	11·8	10·9	19·7	0·84	26·6	—
	14·8	16·3	13·8	16·48	26·7	27·1
	14·8	18·6	17·2	9·31	26·7	26·6
	14·8	11·9	19·7	0·67	26·7	—
Thomas steel axle	17·6	20·4	16·3	[9·58]	40·1	—[1]
	17·6	—	26·2	0·62	40·1	—
	17·6	20·8	19·7	9·04	40·1	41·0
	17·6	—	26·2	0·22	40·1	—
	17·6	—	26·2	0·06	40·1	—
Thomas steel rail	19·0	24·0	16·4	10·19	39·0	39·4
	19·0	17·6	19·7	7·91	39·0	37·7
	19·0	—	26·2	0·57	39·0	—
	19·0	—	26·2	0·56	39·0	—
Mild-steel boiler-plate	17·6	18·0	18·4	4·85	26·6	—
	17·6	—	21·0	0·40	26·6	—
	17·6	—	21·0	0·49	26·6	—
	17·6	—	21·0	0·88	26·6	—
	17·6	18·4	16·4	6·34	26·6	—
	17·6	—	18·7	0·40	26·6	—
	17·6	18·0	16·4	[6·54]	26·6	—[1]
	17·6	16·0	18·7	[4·87]	26·6	—[1]

[1] Not broken in endurance test.
[2] Elastic limit rose to 16·7, and then fell near the end of the endurance test.

250. *Results obtained by Osborne Reynolds and Smith.*—These were obtained with the 'throw testing-machine,' the stress being alternately tension and thrust, and they differ from other results in this, that the speed was much higher, there being 1,000 to 2,000 reversals per minute.

The following table contains the results of tests in which the bars bore about a million or more reversals of stress before breaking. Speaking generally, the range of stress is lower than in Wöhler's tests. But whether this is simply an effect of the speed or is due to other causes, such as increasing vibration at high speed, is not clear.

TABLE X. REVERSALS OF STRESS (REYNOLDS AND SMITH)

Material	Statical tensile strength, tons per sq. in.	Max. stress	Min. stress	Range of stress, tons per sq. in.	Reversals before fracture
Mild steel	24·5	+ 6·72	− 5·96	12·68	2,025,000[1]
„ „	24·5	11·41	9·64	21·05	1,141,000
Mild steel annealed	25·8	6·51	5·74	12·25	1,138,000
„ „	25·8	7·79	6·82	14·61	1,840,000
„ „	25·8	9·88	8·64	18·52	783,000
Lowmoor iron	23·1	+ 6·21	− 5·48	11·69	1,236,000
Cast steel annealed	48·0	+ 6·29	− 5·56	11·85	1,327,000
„ „	48·0	9·74	8·39	18·13	2,270,000
„ „	48·0	10·64	9·00	19·64	918,000
Cast iron	9·4	+ 3·10	− 2·62	5·72	620,000

[1] Not broken.

251. *Tests of Reversal of Stress by Dr. Stanton and Mr. Bairstow.*[1]—These tests were made on the machine at the National Physical Laboratory already described.

There were 800 reversals of stress per minute, and the ratio of tension to thrust was 1·4 to 1. The test bars were ¼ inch in diameter over a length of ½ inch. Tests were made with various intensities of stress, and the number of reversals before fracture was ascertained. From these results the maximum stress which could be sustained for one million reversals was determined.

[1] *Proc. Inst. Civil Eng.*, clxvi.

TABLE XI. MAXIMUM LIMITS OF RESISTANCE FOR ONE MILLION REVERSALS OF STRESS (STANTON AND BAIRSTOW)

Material	Statical tensile strength, tons per sq. in.	Elongation in 8 ins. per cent.	Alternating stresses, tons per sq. in.		
			Tension	Thrust	Range
Swedish Bessemer steel, No. 3	47·6	12·9	18·4	13·1	31·5
" " " No. 2	43·8	17·0	17·7	12·7	30·4
" " " No. 1	28·5	22·8	15·6	11·2	26·8
" charcoal iron	19·6	33·8	11·1	7·9	19·0
Piston rod steel	43·9	18·1	16·5	11·8	28·3
Steel forging	29·5	16·6	12·0	8·6	20·6
Mild steel, No. 2	28·3	24·6	15·1	10·8	25·8
" " No. 1	21·9	28·0	11·0	7·9	18·9
Wrought iron, No. 2	25·6	23·8	11·2	8·0	19·2
" " No. 1	23·8	27·0	12·6	9·0	21·6

252. *Repetition of Alternating Stress at Different Temperatures.*—The author carried out a series of tests on revolving bars fixed at one end and loaded at the other, and maintained at different temperatures. An air bath round the bars was maintained at an approximately constant temperature during the day. The tests were stopped at night when they could not be watched. Broadly, it was found that the hot bars stood variations of stress rather better than cold bars, a result probably due to the annealing effect each evening when the bars were left to cool. The bars were of mild steel, ½ inch in diameter, and the load acted at a leverage of 12 inches.

REPETITION OF STRESS AT DIFFERENT TEMPERATURES

Stress, tons per sq. in.	Range of stress, tons per sq. in.	Revolutions before fracture	Mean temperature F.°	—
± 14·25	28·5	1,001,461	Cold	
14·78	29·6	1,037,093	"	
15·36	30·7	448,622	"	
14·91	29·8	1,094,580	202	
14·91	29·8	1,041,440	349	
14·81	29·6	587,240	449	
± 15·01	30·0	615,518	Cold	
15·02	30·0	790,900	"	
15·01	30·0	604,600	"	
15·16	30·3	280,550	"	
15·00	30·0	172,824	"	
15·01	30·0	[953,944]	400	Not broken
15·01	30·0	[953,944]	"	" "
15·02	30·0	[953,944]	"	" "
15·02	30·0	633,000	"	
15·16	30·3	560,000	"	
15·16	30·3	595,000	"	

Revolutions about 150 per minute.

253. *General Conclusions as to Fatigue of Materials.*— The principal observations on repetition of stress have now been brought together and reduced to common measures, because the question of safe limits of stress is of the highest importance, and while experiments of this kind are difficult and take much time, the number and consistency of the results is very impressive. The diminution of the number of repetitions which cause fracture as the range of stress increases implies that whatever the cause of the decreased life of the material, it is a cause which acts regularly, altering in some way the structure of the material.

The fatigue of the material shown in decreased life as the range of stress increases is not concomitant with a decrease of the statical strength or ductility. A bar subjected to so many repetitions of straining that it is known to be near breaking, or a piece of a bar previously broken by repetition of straining, shows in an ordinary tensile statical test no clear evidence of alteration of strength or ductility.

In certain cases flaws or fissures have been found to be present in bars subjected to so many repetitions of load that they were on the point of breaking. It is at least conceivable that the repetition of stress picks out sections of weakness in the bar, and that the deterioration is almost confined to such planes; the deterioration may be primarily a loss of power of yielding in the particles near the plane of weakness, and not a loss of tenacity. Such a loss of ductility at a section might well show itself finally in a rapidly-spreading fissure or crack. This explanation is hypothetical, but it is at least in accordance with a very curious fact observed in the fracture of bars in Wöhler machines. Such bars after fracture usually show no trace of drawing out, however ductile the material may be, when tested statically. The bars break as if the material was perfectly brittle. This peculiar fracture, without indication of any plastic drawing out, is not uncommon in fractures of tyres, axles, and other structures in ordinary experience.

The author has left the preceding paragraph as orginally written twenty years ago. Since then Dr. Stanton and Mr. Bairstow [1] have proved by microscopic examination that the weakening of bars by repetition of stress is due to slips along the cleavage planes of the crystalline molecules. They state that on the surface of the bars slip lines gradually appeared, broadening out and then becoming massed together and

[1] *Proc. Inst. Civil Eng.* clxvi,

developing into a crack. In many cases the first sets of slip lines observed were not those along which ultimate fracture occurred. It was impossible to detect till near the end of a test which group of slip lines would develop into the crack which caused fracture of the specimen.

The remarkable researches of Bauschinger first indicated that in bars subjected to cyclical variations of stress the elastic limits in tension and compression took new positions. Treating thrust as negative tension, then the elastic limits might both be raised or both lowered. The new limits may be termed natural elastic limits for the given conditions of straining.

It occurred to Bauschinger to suggest that if the range of stress fell within the natural elastic limits the bar would sustain an indefinite number of repetitions, but that if the range of stress exceeded the range between the natural elastic limits the bar would break sooner or later with repetition of straining. Later researches confirm this.

Dr. Stanton and Mr. Bairstow have determined the elastic limits of three bars of Swedish Bessemer steel which had been subjected to more than a million and a quarter reversals of stress. The results are given in the following table :

Elastic Limits after Reversals of Stress

Bar	Tons per sq. in.						
	Primitive elastic limit in tension	Alternating stresses		Elastic limits after reversals		Range of alternating stress	Range between natural elastic limits
		Tension	Thrust	Tension	Thrust		
A	27·7	18·3	13·1	17·3	—	31·3	
B	25·0	16·9	12·0	16·4	—	29·1	29·0
C	25·0	16·9	12·0	—	12·6	29·1	

In Chapter V, § 81, an account has been given of Mr. Bairstow's research[1] on the change in position of the elastic limits with cyclical variations of stress. Fig. 186, taken from his paper, shows a comparison of the range of variation of stress, for which the hysteresis loop disappears, and the limiting range found by Wöhler which materials would stand without fracture. The abscissæ of the curves are the lower limits, and the ordinates the corresponding elastic ranges or safe ranges for an unlimited number of repetitions of straining.

[1] Elastic limits of Iron and Steel under cyclical variations of stress. *Phil. Trans.*, v. 210, pp. 35–55.

The abscissa for the point where the range is zero is the statical tensile breaking stress. The dotted line A B is at 45° with the axis. The agreement of the two sets of curves is remarkably close.

254. *Gerber's Parabola.*—Suppose the ranges of stress for unlimited repetition known for any material. Then if the

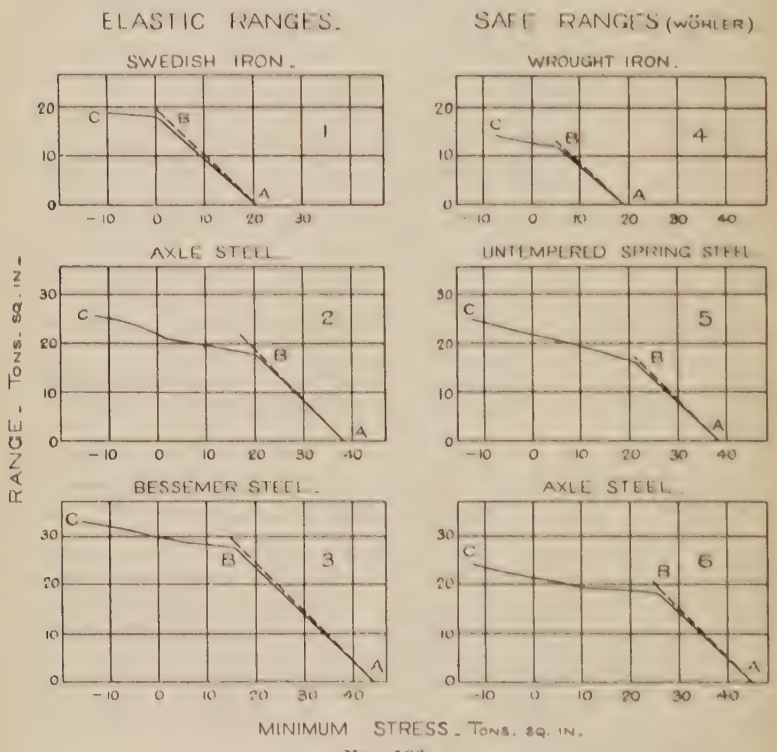


FIG. 186.

ranges of stress are plotted as ordinates, and the minimum stress as abscissæ, the points fall approximately on a parabolic curve.

Let f_{max}, f_{min} be the limits of stress, and $\Delta = f_{max} \mp f_{min}$ be the range of stress. The upper sign is to be taken if the stresses are of the same kind, and the lower if they are of different kinds. Let f be the statical breaking strength. Then Gerber's equation is—

$$f_{max} = \frac{\Delta}{2} + \sqrt{f^2 - n'\Delta f},$$

where n is a constant for any given material, ranging from 1·5 in ductile iron and steel to 2 in harder qualities. The following table gives values of f and n deduced from Wöhler's and Bauschinger's endurance tests, in which the bars stood

TABLE XII. GIVING THE MAXIMUM AND MINIMUM STRESS, AND RANGE OF STRESS, FOR BARS WHICH STOOD AT LEAST TWO OR THREE MILLION CHANGES OF LOAD BEFORE BREAKING

(Stresses in tons per square inch)

Material	Minimum stress	Maximum stress	Range of stress	Authority
Phœnix iron	− 8·6	+ 8·6	17·2	Wöhler
"	+ 0	+ 15·25	+ 15·25	
"	12	20·5	10	$n = 1·33, f = 22·8$
"	22·8	22·8	0	
Krupp's axle steel	− 14·05	+ 14·05	+ 28·10	Wöhler
" "	0	20·5	26·5	
" "	17·5	37·75	20·25	$n = 1·83, f = 52$
" "	52	52	0	
Untempered spring steel	0	25·5	25·5	Wöhler
" "	12·5	35·0	22·5	
" "	20	40	20	$n = 2·14, f = 57·5$
" "	30	45	15	
" "	57·5	57·5	0	
Wrought-iron plate	− 7·15	+ 7·15	14·30	Bauschinger
" "	0	13·10	13·10	
" "	11·4	19·2	7·8	$n = 1·60, f = 22·8$
" "	22·8	22·8	0	
Bessemer steel	− 8·55	+ 8·55	17·10	Bauschinger
" "	0	15·7	15·7	
" "	14·3	23·8	9·5	$n = 1·68, f = 28·6$
" "	28·6	28·6	0	
Bar iron	− 7·85	+ 7·85	15·7	Bauschinger
"	0	14·4	14·4	
"	13·3	22·02	8·72	$n = 1·67, f = 26·0$
"	26·0	26·0	0	
"	− 8·65	+ 8·65	17·3	Bauschinger
"	0	15·75	15·75	
"	13·2	21·92	8·72	$n = 1·53, f = 26·4$
"	26·4	26·4	0	
Steel axle	− 10·5	+ 10·5	21·0	Bauschinger
"	0	19·7	19·7	
"	20	32·1	12·1	$n = 1·91, f = 40$
"	40	40·0	0	
Steel rail	− 9·7	+ 9·7	19·4	Bauschinger
"	0	18·4	18·4	
"	19·5	30·85	11·35	$n = 2·00, f = 39$
"	39	39	0	
Steel boiler-plate	− 8·65	+ 8·65	17·3	Bauschinger
"	0	15·8	15·8	
" "	13·3	22·55	9·25	$n = 1·53, f = 26·6$
" "	26·6	26·6	0	

Where the range of stress is zero, the stress given is the ordinary statical breaking weight.

WÖHLER'S AND BAUSCHINGER'S ENDURANCE TESTS.

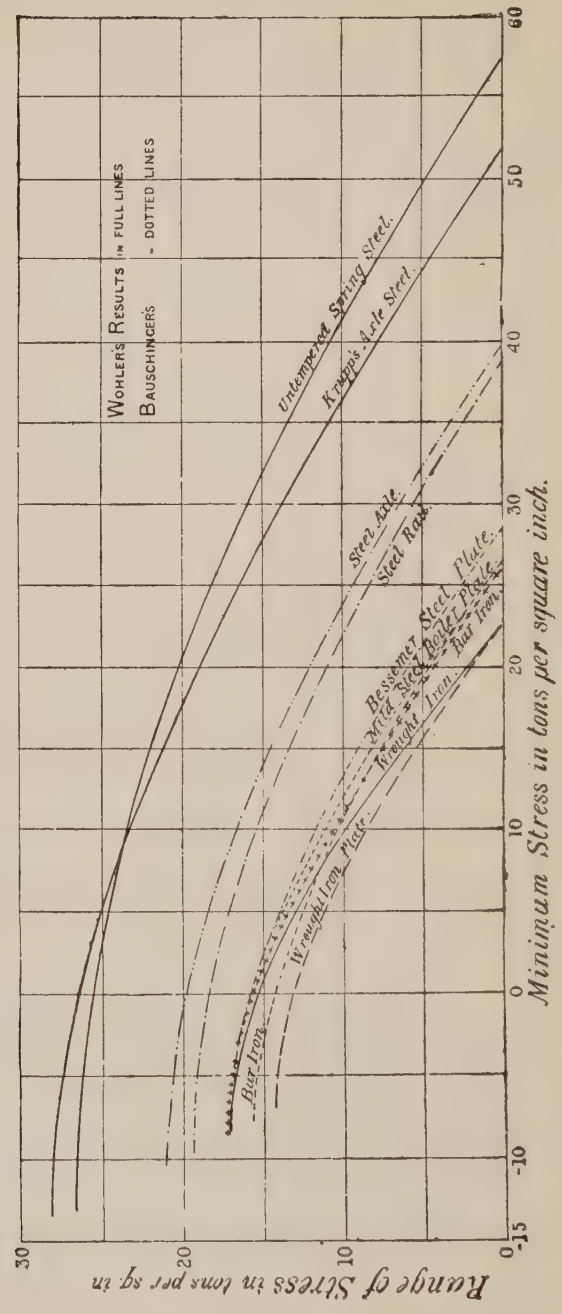


FIG. 187.

over 5 millions of repetitions of load. From the values so deduced the parabolas in fig. 187 have been plotted. It will be seen that these quite independent experiments give consistent values for the ranges of stress under all conditions of loading.

The following tables give the values of f_{max} and f_{min} for the most useful cases, recalculated from the same equations. The last column is of course the experimentally determined breaking strength of the material used:

TABLE XIII. BAUSCHINGER'S ENDURANCE TESTS

(Stresses requiring 5 to 10 million repetitions to cause fracture. Tons per sq. in.)

Material	Opposite stresses		One stress zero		Similar stresses		Range zero. Ultimate statical strength
	Least	Greatest	Least	Greatest	Least	Greatest	
Wrought-iron plate	− 7·15	+ 7·15	0	13·10	11·4	19·2	22·8
Bar iron	− 7·85	+ 7·85	0	14·4	13·3	22·02	26·6
Bar iron	− 8·65	+ 8·65	0	15·75	13·2	21·92	26·4
Bessemer mild steel plate	− 8·55	+ 8·55	0	15·70	14·3	23·8	28·6
Steel axle	− 10·5	+ 10·5	0	19·70	20·0	32·1	40·0
Steel rail	− 9·7	+ 9·7	0	18·4	19·5	30·85	39·0
Mild-steel boiler-plate	− 8·65	+ 8·65	0	15·8	13·3	22·55	26·6

TABLE XIV. LIMITS OF STRESS, FROM WÖHLER'S ENDURANCE TESTS

(Stresses, in tons per sq. in., for which fracture occurs only after an indefinitely large number of repetitions)

Material	Opposite stresses		One stress zero		Similar stresses		Range zero. Ultimate statical strength
	Least	Greatest	Least	Greatest	Least	Greatest	
Wrought iron	− 8·6	+ 8·6	0	15·25	12·0	20·5	22·8
Krupp's axle steel	− 14·05	+ 14·05	0	26·5	17·5	37·75	52·0
Untempered spring steel	− 13·38	+ 13·38	0	25·5	12·5	34·75	57·5

The following are the values of the constants in Gerber's equation deduced from the results of Dr. Stanton and Mr. Bairstow:

STANTON AND BAIRSTOW'S TESTS. ONE MILLION REVERSALS

	f	n
Swedish steel, No. 3	47·6	1·47
„ „ No. 2	43·8	1·47
„ „ No. 1	28·5	1·12
Swedish charcoal iron	19·6	1·07
Piston rod steel	43·9	1·57
Steel forging	29·5	1·47
Mild steel, No. 2	28·3	1·09
„ „ No. 1	21·9	1·16
Wrought iron, No. 1	25·6	1·28
„ „ No. 2	23·8	1·24

Some of the values of n are lower than Bauschinger's. This may be due to the number of reversals being limited to one million, or possibly to the greater speed of reversal.

255. *General Considerations on Safe Working Limits of Stress.*—The recognition of the importance of Wöhler's results has been hindered by the existence of officially sanctioned rules prescribing fixed limits of working stress depending on the material only and ignoring the conditions of straining. It has been a common practice to divide the statical breaking strength by some fixed 'factor of safety' to determine the safe working stress, and it has been tacitly accepted that the factor of safety measures the margin between the working and breaking load. There are undoubtedly contingencies such as variation in the quality of materials, imperfections of workmanship, and wear or corrosion, which may properly be allowed for by a factor suitable to different cases. But it would be impossible with these contingencies alone in view even to explain the wide differences of working stress in different cases which experience has led engineers to adopt. If Wöhler's law is true, it is false to reckon as a margin of security the difference between the working stress and the statical strength.

Previous to 1849 no defined rule, recognised officially, appears to have existed, limiting the discretion of the engineer in the design of bridges and other structures. In 1847 a Royal Commission was appointed to inquire into the conditions which should be observed in the application of iron to structures. The Commission reported against fettering engineers by legislative enactments. But they made some

recommendations with respect to cast-iron bridges which were adopted as rules by the Board of Trade. According to these recommendations, the breaking weight of a cast-iron bridge was to be six times the live load added to three times the dead load. They also recommended that an allowance should be made for dynamic action in bridges of less than 40 feet span. A discussion arose shortly afterwards as to the safety of the Torksey Bridge, and then, for the first time, a proposal was made to limit the stress in all wrought-iron bridges to 5 tons per sq. in. In 1858 a further dispute arose as to the safety of a bridge over the Spey. An attempt was made to get the Board of Trade to allow for wrought-iron bridges, as for cast-iron, a different factor of safety for the stresses due to the dead and live loads. But the Board of Trade then formally adopted the rule that the stress in wrought iron should not exceed 5 tons per sq. in. Later, for steel bridges, a limiting stress of 6½ tons has been allowed, under certain restrictions as to the testing of the material.

It will be seen that as early as 1847 the Railway Commission recognised a difference between the action of a dead and a live load. Unfortunately, they were disposed to ascribe this difference entirely to the dynamical action of the live load causing increased deflection, and therefore increased stress. Since the publication of Wöhler's results, a quite different view of the difference between the action of a fixed or dead and a varying or live load has been recognised by the more thoughtful engineers.

In both structures and machines the working stress has been diminished in cases where the range of variation of stress is large. For example, Sir B. Baker stated that the short spans of the Elevated Railway of New York, where the ratio of live to dead weight is large, were designed for a stress of 3·6 tons per sq. in. on the flanges, 3·4 tons on the web bracing, and 2·0 tons for members subjected to alternate tension and compression; that a recent German bridge over the Danube was designed for limits of stress varying with the range of stress from 3·1 tons to 5·8 tons per sq. in.; and that a Hungarian bridge over the same river was designed for stresses varying from 3·9 to 5 tons per sq. in. On the other hand, Sir B. Baker estimates that on the Conway Bridge, which carries the heavy traffic to the London and North Western, and in which the ratio of dead to live load is large, the stresses reach the value of nearly 6 tons per sq. in.

There is general agreement now that Wöhler's law fixes the breaking strength in the case of complete reversals of stress, and that members subjected to such reversals should be designed with reference to it. But a limitation has been suggested to the application of Wöhler's law in the case of varying stress of one kind. It has been urged that in any case the primitive yield stress is the maximum stress which can in any case be permitted, otherwise deformations would

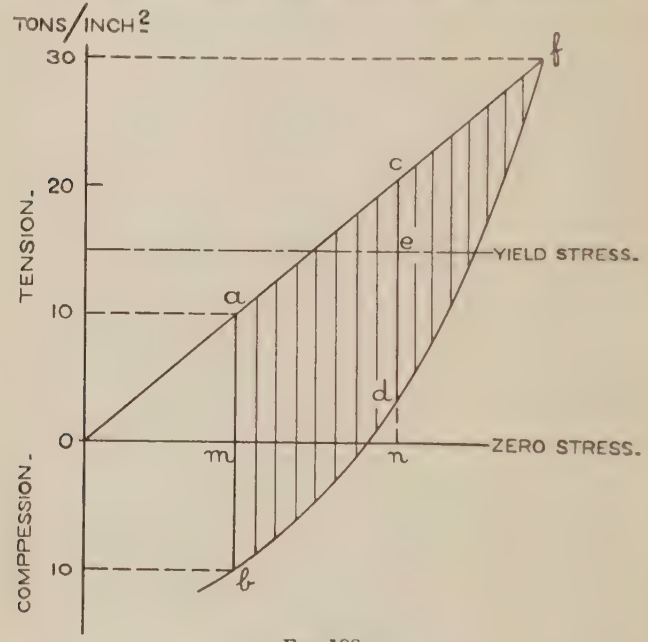


FIG. 188.

be caused ruinous to any structure. The author does not think the argument convincing, or, at all events, that it is stated too absolutely. The point can be made clearer by plotting repetition results in another way. Fig. 188 shows roughly a plotting of results for mild steel, in which both maximum and minimum stresses are set up vertically. The maximum stresses are the ordinates of the straight line af, the corresponding ordinates of the curve fb are the minimum stresses. The range of stress is the vertical intercept between af and bf. Here f corresponds to the statical tensile strength. ab is the range of stress for complete reversals,

the maximum and minimum stresses $m\,a$, $m\,b$ being equal. Consider a case of varying tension where the maximum and minimum stresses by Wöhler's law are $n\,d$, $n\,c$, and the range of stress which would be sustained indefinitely is $c\,d$. It is urged by some engineers that if $n\,e$ is the primitive yield stress, the maximum practical stress is $n\,e$, for if this is exceeded there would be dangerous deformation. Now (*a*) this does not apply to such cases as that of a crane chain, which is subjected to tension only. An elongation of the chain is not prejudicial to its use. Its resistance to shocks may be reduced by permanent elongation, but its strength for carrying the working load for which it is designed is not impaired if the maximum stress does not exceed $n\,c$. (*b*) In the case of ordinary machine parts and structures it is generally only indefinitely short portions—the bottom of a screw thread, or the line of fracture of a riveted joint—which are subjected to the maximum stress. It is not clear that the yielding of these indefinitely short portions impairs the structure. They yield, acquire a new elastic limit, and the strength, if Wöhler's law is not transgressed, is unimpaired by the yielding.

There does not appear to be any satisfactory reason for taking in these cases the working stress less than $n\,c$, except to allow for uncalculated contingencies.

CHAPTER XVII

TIMBER

256. Unlike the materials hitherto examined, timber has, in consequence of its organic origin, a remarkable and definite structure, so that its mechanical properties cannot be understood without reference to its mode of growth. Nor is this all. The quality of timber is largely influenced by the soil and climate, the age of the tree and the season of felling, and the duration of the seasoning process. Hence, experiments on timber, to be valuable, should be made on logs the history of which is known, and should be directed so as to determine the relative influence of all the circumstances which affect its mechanical properties.

Timber is composed of vegetable cells, and, chiefly, very elongated cells, termed wood-fibres, arranged nearly parallel to the axis of the stem. A stress applied to a transverse section must break the fibres across, while a stress applied to a longitudinal section separates them from each other. The strength along the grain depends on the strength of the fibres; that across the grain on their adhesion. Hence, in pine wood the lateral strength is only one-tenth to one-twentieth of the longitudinal; in leaf-wood, one-sixth to one-fourth. All the timber commonly used in construction is derived from exogenous trees. In the section of an exogenous stem there may be recognised the pith, the woody tissue forming the greater part of the section, and the bark. The growth of the stem occurs by the addition, annually, of a ring of new fibres between the bark and the already formed timber. Hence most exogenous stems indicate, by distinct annual rings, the age of the tree. The timber is sometimes broadly marked, so as to be distinguishable into two portions—the heart-wood and sap-wood; and usually, but not invariably, the sap-wood is weaker and less sound than the heart-wood. In some trees, plates of cellular tissue

extend radially from the pith towards the bark. These are termed medullary rays, and are planes of weakness in the timber.

Timber is broadly distinguished into soft wood and hard wood. The difference roughly agrees with a distinction between timber derived from the needle-leaved trees (coniferous trees) and timber derived from broad-leaved trees. By far the largest part of the timber used in construction is the soft wood derived from needle-leaved coniferous trees. In Europe the most important timber tree is the northern pine (*Pinus sylvestris*), yielding timber known as red or yellow fir, Memel, Dantzig, or Riga fir, or yellow deal. Next to this the spruce fir (*Abies excelsa*) yields the valuable timber known as white deal. Similar timber, coming from America, the produce of allied species, is commonly known as pine. The yellow pine of the pattern maker and the pitch pine of the joiner are examples. All timber, after felling, requires to be seasoned, and in ordinary seasoning timber loses one-fifth to one-seventh of its weight. When perfectly dried, it may lose one-third of its weight. During seasoning it shrinks, and more in a transverse direction, and along the annual rings, than longitudinally. A plank of oak may shrink in width one-twelfth, and one of pine or fir one-thirtieth to one-fortieth. This shrinkage, which continues a long time, is one of the determining conditions in the arrangement of timber in construction. It is during seasoning that the shrinkage causes the heart-shakes (radial) or cup shakes (along the rings) which detract from the value of timber.

Till recently, tests of timber have been made on comparatively small specimens. Such test specimens are virtually selected, not average, specimens. They are more homogeneous and better seasoned than larger pieces, and are free from knots, shakes, and other serious defects. Hence they give values for the strength of the timber in excess of the strength of large pieces. To furnish the most useful data for construction, tests should be made on large pieces. The following short table gives the general relation of the strengths for a few of the more important timbers:

PROPERTIES OF TIMBER, FROM SMALL TEST SPECIMENS

Kind of timber	Weight in lbs. per c. ft.	Coefficient of elasticity, tons per sq. in.	Tensile strength along the fibre, tons per sq. in.	Crushing strength along the fibre, tons per sq. in.	Coefficient of bending strength, tons per sq. in.	Shearing resistance along the fibre, tons per sq. in.
British oak	50–54	656	6·70	4·46	5·27	1·03
Beech	43	603	5·05	3·16	4·70	0·40
Spruce	28–30	715	5·50	2·86	3·77	0·27
Yellow pine	34–37	—	—	2·46	3·68	—
Red pine	30–38	750	5·80	2·59	3·71	0·29
Elm	34	445	6·25	4·60	3·50	0·62
Pitch pine	39–44	—	5·09	3·99	3·57	—
White pine	25	—	5·10	2·24	3·03	—
Mahogany	35–53	560	5·51	3·30	4·46	—
Lignum vitæ	60–83	—	7·14	4·40	7·18	—
Teak (Indian)	41–55	1,071	6·70	5·36	6·92	—
Jarrah	62–65	620	7·20	3·04	4·13	—
Karri	60–63	760	6·20	2·92	—	—
Iron bark	74	1,070	8·05	4·47	8·15	—
Blue gum	63	910	9·00	3·36	5·86	—

257. *Variation in Quality of Timber.*—The strength of timber varies with the locality where the tree grew, the part of the trunk from which the specimen was taken, and other conditions. The following table, containing a summary of about 2,000 tests from twenty-six different trees, shows how large this variation may be:

TESTS OF LONG LEAF PINE. (*Pinus palustris*)

Report to U.S.A. Department of Agriculture

—	Heaviness, lbs. per c. ft.	Coefficient of elasticity from bending test, tons per sq. in.	Coefficient of bending strength, tons per sq. in.	Crushing strength, tons per sq. in.	Tensile strength, tons per sq. in.	Shearing strength, tons per sq. in.
Butt logs	28–64·8	500–1,380	2·12–7·25	2·13–4·40	3·84–14·4	·21–·58
Middle logs	36 53·5	510–1,360	3·40–7·65	2·25–4·15	2·82–13·4	·24–·55
Top logs	32–56·5	375–1,200	1·90–7·00	2·04–4·06	1·85–10·8	·22–·52

258. *Determination of the Density or Heaviness of Timber.*—The density of timber is easily ascertained by measuring and weighing carefully planed rectangular test blocks. Let b, t, and h be the mean breadth, thickness, and height of a rectangular block, in inches, from several measurements. Then the volume of the block is $b\ t\ h\ /\ 1{,}728$ cubic feet. If

w is the weight of the block in lbs., then the heaviness is $1{,}728w / b\ t\ h$ lbs. per cubic foot. A more rapid method of ascertaining the heaviness is to weigh the block and also the volume of water it displaces. Let w be the weight of the block; w_w the weight of the volume of water it displaces in lbs.; G the weight of a cubic foot of water in lbs. (62·4 at normal temperature). Then w_w/G is the volume of the block

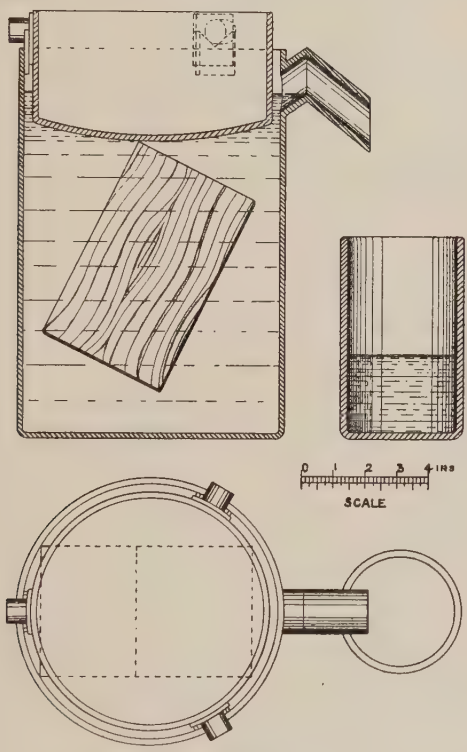


Fig. 188A

in cubic feet and Gw / w_w is the heaviness in lbs. per cubic foot. For exactness the weight of a cubic foot of water in lbs. at the temperature of the water used must be taken from well-known tables.

A convenient apparatus for determining the volume of water displaced by a block is shown in fig. 188A. It consists of a thin brass cylindrical vessel with a spout, and a cover which can be very exactly depressed into it. The cover has

three cylindrical pins, which rest in three V's on the vessel. The vessel is first nearly filled with water, and the cover put in place. Any overflow is allowed to go to waste. The cover is then gently raised, the wood block put in the vessel, and the cover replaced. All the water displaced in this operation is carefully collected and weighed. It is a quantity of water the volume of which is equal to the volume of the timber block.

259. *Percentage of Moisture.*—The density of timber is greater and the strength less as the percentage of moisture is greater. The percentage of moisture is determined by weighing, before and after drying at 200° to 212°, either shavings drilled out of a test block or thin sawn discs $\frac{3}{4}$ to $1\frac{1}{2}$ inches thick. The drying should be continued, in a drying oven with free air circulation, till there are no differences of weight greater than 0·5 per cent. in 24 hours. The percentage of moisture is calculated on the weight of the dry wood. If w_w is the weight before drying and w_d after drying, then $w_w - w_d$ is the amount of moisture, and $100\ (w_w - w_d)\ /\ w_d$ is the percentage of moisture. The normal percentage of moisture in air-dried timber, to which density and strength values should be reduced, is taken to be 12 per cent.

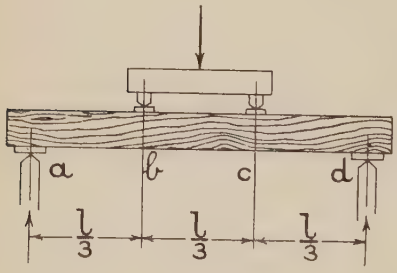


Fig. 189.

In some bending tests of pine wood, the coefficient of elasticity was 17 per cent., the elastic strength 50 per cent., and the breaking strength 33 per cent. less in wet timber than in carefully air-dried timber.

260. *Bending Tests.*—Bars of rectangular section carefully planed and squared at the ends are used, and a sketch should be made of the direction of the grain at the ends. Usually the bar or beam is supported at the ends and loaded at the centre. To distribute the pressure at the loading and supporting points metal or hard wood plates are used of an area about equal to the cross-section of the bar. The observations should include the load and deflection at the

proportional limit, the breaking load and deflection and the mode of fracture.

As timber is not homogeneous, it is sometimes considered desirable to spread the maximum bending moment over the middle third of the bar by the so-called third point loading (fig. 189). The load is distributed to two points, dividing the span into three equal segments.

The deflection is most easily observed by fixing a scale divided into $\frac{1}{100}$ths of an inch at the centre of the test bar and reading the deflection by a small telescope carried by a bar resting on the end supporting knife-edges (§ 151). Sometimes a fine wire kept taut by a spring is stretched between two nails driven into the timber over the supports, and the deflection is read on a scale fixed to the beam at the centre.

Failure in a bending test may occur by tearing at the tension side, by crippling or crushing at the thrust side, or by shearing along horizontal planes near the neutral axis and generally near the ends of the beam.

EQUATIONS FOR BENDING TESTS

Let P_e be the load at the proportional limit; P_b the load at fracture; (in third point loading P_e and P_b are the sums of the loads at the two loading points;) l = span between supports; b = width and h = depth of section of bar; δ = deflection at centre at the proportional limit.

For central loading—

$$\text{Greatest shearing stress} = (\tfrac{3}{4} \cdot P_b) \,/\, (b\,h)$$
$$\text{Stress at elastic limit} = (\tfrac{3}{2}\, P_e\, l) \,/\, (b\,h^2)$$
$$\text{Coefficient of elasticity} = (\tfrac{1}{4}\, P_e\, l^3) \,/\, (b\,h^3\,\delta)$$
$$\text{Modulus of rupture} = (\tfrac{3}{2}\, P_b\, l) \,/\, (b\,h^2)$$

For third point loading—

$$\text{Greatest shearing stress} = (\tfrac{3}{4}\, P_b) \,/\, (b\,h)$$
$$\text{Stress at elastic limit} = (P_e\, l) \,/\, (b\,h^2)$$
$$\text{Coefficient of elasticity} = (0{\cdot}213\, P_e\, l^3) \,/\, (b\,h^3\,\delta)$$
$$\text{Modulus of rupture} = (P_b\, l) \,/\, (b\,h^2)$$

261. *Compression Tests.*—These are usually made either on cubes or on prisms 3 × 3 × 9 inches, or larger, with the

load acting along the fibres. The seating at one end of the test block should have a spherical joint. Failure takes place usually by shearing along a plane at about 45° with the axis, but sometimes by longitudinal splitting. As the rate of loading somewhat influences the result, it has been suggested to limit the rate of loading to about 300 lbs. per sq. in. per minute.

262. *Abrasion Tests.*—Small blocks of wood are fixed in clamps and held with a prescribed pressure against a revolving table covered with fine sand paper such as is used for finishing wooden articles. A block of a standard wood is tested at the same time and the relative wear is ascertained. In the United States the standard wood is maple, air-dried to 12 per cent. moisture. The abraded area of the blocks is 2×2 inches, and the pressure on each block 26 lbs. Speed of rotation, 68 revolutions per minute.

263. *Bauschinger's Investigation of the Elasticity and Strength of Pine Wood.*—In Bauschinger's[1] earlier investigation the object was to determine the conditions which should be observed in testing timber, the relative value of different modes of testing, the influence of conditions of growth, time of felling, and seasoning on the strength of timber, and the relations between the physical constants of the material. The amount of moisture in the timber was found to have a very great influence on its density and strength, so that comparative values could only be obtained by reducing experimental results to a uniform standard dryness. The dryness was determined for every test piece. At first this was done by taking a few grams of sawdust, raspings, or chips from the timber drying them at 101° C. in a current of dried air for about eight hours, and then re-weighing to determine the loss. In later trials the whole test specimen was dried in an oven kept at 101° to 105° till it ceased to lose weight. The drying usually lasted two to four days. To determine at all accurately the strength or density at a standard dryness, it is necessary to experiment on three test specimens in three stages of dryness. If the results are plotted, a curve can be drawn giving the relation of strength or density to dryness, and from this the required value at standard dryness can be determined. Bauschinger takes 15 per cent. of moisture as the most convenient standard dryness, that being

[1] *Mittheilungen aus dem Mech. Techn. Laboratorium in München*, 1883 and 1887.

the condition most often reached by simple exposure to air.

The bending tests were made on beams about 20 inches square and 9 feet long. These were broken with a clear span of 98·4 inches. The tension tests were made on small test bars, and with the shackles shown in fig. 100. The elastic limit in tension almost coincides with the breaking point. The coefficient of elasticity was determined from the extension with a load of about one-third the breaking load.

The tension results show very great differences, due partly to the small section of the test pieces, which allowed the greatest influence to original differences of quality in the timber. The tenacity is very great, extraordinarily so if the large amount of vacant space is allowed for which is observable in microscopic sections. Pieces cut near the heart of the tree are weaker than pieces cut near the periphery; and this is connected generally, but not always, with less density in the wood near the heart. The strength does not directly depend on the width of the annual rings. But it appears to depend on the proportionate width of the summer zone of the annual rings as compared with the spring zone. In tension experiments the influence of time of felling is not recognisable a short time after felling. The coefficient of elasticity varies very significantly with the strength, increasing and decreasing with it. The bending tests on beams of the full useful section of the log showed, generally, that the strength and coefficient of elasticity varied directly with the density. The results were, however, influenced by the presence of knots and other defects. The pressure tests gave, on the whole, the most uniform results, the section of the test pieces being fairly large, and a uniform distribution of stress being fairly well obtained. But the elastic limit and coefficient of elasticity are difficult to ascertain accurately in pressure tests. The strength increases with the density, but the heart pieces are weak. In timber tested within three months of felling, the winter-felled timber was 25 per cent. stronger than summer-felled. But later researches showed that this difference disappeared after a longer time of seasoning. The strength increases in seasoning, but the increase probably ceases after about one year.

Bauschinger concludes that when the question is the average quality of a timber, as in inquiries with reference to

the influence of time of felling or seasoning, or the influence of the soil or locality of growth, then the pressure tests are the easiest and most trustworthy. Discs about 6 inches thick should be sawn from each end and the middle of the log, and these then divided into four sectors. From each of these a square prism should be cut, the height being $1\frac{1}{2}$ times the length of side. The compressive strength should then be ascertained for as nearly as possible the standard dryness (15 per cent. of moisture). The test pieces should be measured, and weighed to determine the density. The coefficient of elasticity is best determined from bending tests of a beam of the whole useful section of the log. As this depends on the quality of the whole section, and is determined for stresses within the elastic limit, it is probably a very valuable indication of the structural value of the timber. By plotting his results, Bauschinger shows that there is a definite relation between the coefficient of elasticity and the bending and crushing strength, and that this can probably be expressed by a linear equation. There is also a definite relation in pine wood between the density and the strength, expressed by the following equation:

$$= 6{\cdot}35\,\delta - 0{\cdot}635,$$

where β is the crushing strength in tons per sq. in., and δ the density at a standard dryness of 15 per cent.

The following are some of the results in the earlier research, the timber being tested about three months after felling:

TENSION EXPERIMENTS

(Test pieces, 1·6 × 0·4 inch section. Mean values as tested)

Timber	Locality	Summer-felled. Tenacity, tons per sq. in.			Winter-felled. Tenacity, tons per sq. in.		
		Circumference	Heart	Mean of log	Circumference	Heart	Mean of log
Red pine . .	Lichtenhoff .	6·67	1·46	5·01	4·76	1·84	3·78
Spruce . .	Frankenhofen	6·16	1·97	4·76	7·87	2·19	5·97
,, . .	Regenhütte .	6·54	2·60	5·24	6·10	1·90	4·70
,, . .	Schliersee .	6·44	1·84	3·59	3·68	1·62	2·99

PRESSURE EXPERIMENTS

(Test pieces, about 3½ × 3½ inches, and 6 inches long. Mean strength, as tested, and also reduced to a standard dryness—10 per cent. of moisture)

Timber	Locality	Summer-felled. Compressive strength in tons per sq. in.		Winter-felled. Compressive strength in tons per sq. in.	
		As tested	Standard dryness	As tested	Standard dryness
Red pine	Lichtenhoff	1·78 [19]	2·37	2·03 [26]	3·20
Spruce	Frankenhofen	1·56 [20]	2·13	1·99 [17]	2·50
,,	Regenhütte	1·49 [27]	2·41	1·78 [20]	2·43
,,	Schliersee	1·03 [20]	1·41	1·43 [19]	1·89

The figures in brackets give the moisture per cent.

BENDING EXPERIMENTS

(Beams, about 7½ × 7½ inches, and 98 inches span. Mean values. The upper value for each timber is for a summer-, and the lower for a winter-, felled tree)

Timber	Locality	Coefficient of elasticity, tons per sq. in.	Elastic limit, tons per sq. in.	Coefficient of bending strength, tons per sq. in.	Density	Content of moisture, per cent.
Red pine	Lichtenhoff	686	1·28	3·00	0·50	23
,,	,,	654	1·40	2·86	0·55	33
Spruce	Frankenhofen	698	1·45	2·66	0·45	29
,,	,,	737	1·66	2·86	0·45	27
,,	Regenhütte	730	1·37	2·64	0·46	34
,,	,,	698	1·44	2·83	0·43	31
,,	Schliersee	464	0·93	1·87	0·355	23·5
,,	,,	438	0·84	1·63	0·375	25

These results are directly comparable with Lanza's results, given below. These latter were also on pretty large beams.

The influence of a longer time of seasoning is shown in the following table:

AVERAGE CRUSHING STRENGTH OF WHOLE SECTION OF LOG

(Ten per cent. moisture. Tons per sq. in.)

Time of felling	Lichtenhoff		Frankenhofen		Regenhütte		Schliersee	
	A	B	A	B	A	B	A	B
Summer-felled	2·34	3·21	2·15	2·86	2·37	2·81	1·40	2·04
Winter-felled	3·03	2·83	2·51	2·95	2·39	2·83	1·89	2·13

A. Tested 3 months after felling.
B. Tested 5 years after felling.

264. *American Tests of Timber with Large-sized Test Pieces.*—Tests with large test pieces have been made in the United States, chiefly under the direction of Professor Lanza, at the Massachusetts Institute of Technology.[1]

Professor Lanza appears to have failed to make satisfactory tension experiments on large specimens. He concludes that tie bars used in construction will always give way in some other manner than by direct tearing—for instance, by pulling out the fastenings, and shearing and splitting the timber. Tests of crushing strength are much less difficult. The following table gives a summary of a series of tests of wooden posts, generally 7 to 10 inches in diameter, made for an insurance company under Professor Lanza's direction. In all these tests the strength was simply proportional to the area of cross-section, the deflection laterally being insignificant :

Tests of Wooden Posts and Blocks, usually with Flat Ends (Lanza)

Form	Approximate size		Crushing strength in tons per sq. in.			Coefficient of elasticity, tons per sq. in.
	Length, feet	Section, sq. ins.	Max.	Min.	Mean	
Yellow Pine						
Round . .	12	30–65	2·10	1·63	1·97	728–984
„ . .	12	45–61	2·05	1·82	1·94	949
„ . .	2	48–86	2·10	1·93	2·01	734–1091
Rectangular .	12	100	—	—	2·33[2]	—
„ . .	2	81–103	—	—	2·41	—
Round . .	—	45–48	2·18	1·61	1·90	—
White Oak						
Round . .	12	32–63	1·69	1·34	1·56	545–781
„ . .	2	47–93	1·99	1·40	1·57	493–582
Old and Seasoned White Oak						
Round . .	12	24	2·69	2·05	2·28	823–955
„ . .	12	25	1·89	1·31	1·55[3]	—
„ . .	13	79–87	2·08	1·73	1·92	646–916
„ . .	13½	60–65	2·18	1·53	1·82	—

Another series of tests on large rectangular posts of white and yellow pine timber was made with the Watertown machine. The lengths varied up to 30 feet. The results are

[1] *Applied Mechanics*, Lanza, p. 497. Also, *Report on Strength of Wooden Columns*, Lanza; and Executive Document 12, Forty-seventh Congress, First Session.

[2] One end flat, one with rectangular pintle. [3] Maple cap and oak base.

too numerous to give here, but they have been plotted by Mr. E. F. Ely, of the Massachusetts Institute of Technology, and from the plotting the following rule is derived. The posts had flat ends, and the load was evenly distributed.

Let l be the length, and r the least sectional dimension. Then the crushing stress f in tons per sq. in. of section is as follows :

White pine		Yellow pine	
$\frac{l}{r}$	f	$\frac{l}{r}$	f
0–10	1·116	0–15	1·785
10–35	·893	15–30	1·562
35–45	·669	30–40	1·339
45–60	·446	40–45	1·116
—	—	45–50	·893
—	—	50–60	·669

265. *Bending Tests.*—The following summary gives the more important results of Professor Lanza's bending tests. The beams were 2 to 6 inches wide and 2 to 12 inches deep. The span varied from 4 to 20 feet.

—		Coefficient of bending strength, tons per sq. in.	Coefficient of elasticity, tons per sq. in.
Spruce beams.	Max.	3·910	709
,, ,,	Min.	1·337	401
,, ,,	Mean	2·180	594
Yellow pine beams.	Max.	5·071	1,063
,, ,, ,,	Min.	1·769	519
,, ,, ,,	Mean.	3·255	779
Oak beams.	Max.	3·419	789
,, ,,	Min.	2·225	381
,, ,,	Mean	2·712	577
White pine.	Max.	3·237	572
,, ,,	Min.	1·535	413
,, ,,	Mean	2·146	484

Beams which gave Way by Shearing.—In Lanza's tests six spruce beams and five yellow pine beams gave way by longitudinal shearing near the neutral axis. The intensity of the shearing stress varied from 117 to 248 lbs. per sq. in. in the

spruce beams, and from 153 to 397 lbs. per sq. in. in the yellow pine beams. The mean values were :

	Shearing strength, lbs. per sq. in.	Shearing strength, tons per sq. in.
Spruce beams	191	0·0853
Yellow pine beams	248	0·1107

In the beams which did not fail by shearing the mean intensity of shearing stress was about the same. Hence it may be concluded that, for soft wood timber, beams give way by shearing at the neutral axis or by tearing at the convex surface almost indifferently.

266. *Direct Experiments on Shearing along the Grain.*—Direct experiments on the shearing resistance along the grain were made at the Watertown Arsenal, and gave somewhat higher values of the shearing strength. This is probably due to the fact that, in shearing experiments, the timber is forced to shear at a selected section, while in the beam experiments the shearing occurred along the weakest of the planes near the neutral axis of the beam. The specimens were also comparatively small :

Shearing Tests (Watertown Arsenal)

	Shearing strength, lbs. per sq. in.
Ash	458 to 700
Yellow birch	563 „ 815
White maple	367 „ 647
Red oak	726 „ 999
White oak	752 „ 966
White pine	267 „ 366
Yellow pine	286 „ 415
Spruce	253 „ 374
Whitewood	382 „ 406

The greater shearing strength of the leaf woods is noticeable.

267. *Influence of Time on Bending Strength and Elasticity.*—Experiments by Herman Haupt, and more recent experiments by Thurston [1] and Kidder,[2] show : (1) That the deflection of a beam of pine under a statical load increases with time, or the modulus of elasticity is less for a prolonged than for an immediate loading ; (2) that the beam breaks in course of

[1] *Proc. Am. Assoc. for Advancement of Science*, 1881. *Proc. Inst. C.E.* lxxi. p. 428.

[2] *Journal of Franklin Institute*, 1882. *Proc. Inst. C. E.* lxxi. p. 431.

time with a statical load a good deal less than that required to break it immediately. In Thurston's experiments a plank of yellow pine was selected. Bars $1\frac{1}{4}$ to 3 inches square, and 40 to 54 inches long, gave a density of 0·75 to 1·0, a coefficient of bending strength of 4·91 to 5·36 tons per sq. in., and a coefficient of elasticity of 1,005 tons per sq. in. Kiln dried, the coefficient of bending increased one-fifth, and that of elasticity one-ninth. For a bar 1 inch square on supports 40 inches apart the centre breaking load was 375 lbs. Nine bars of this size were prepared, three being loaded with 350 lbs., three with 300 lbs., and three with 250 lbs., at the centre. All the first three broke in less than 43 hours; all the second three in from 80 to 719 hours; and all the third set, loaded with only 60 per cent. of the immediate breaking weight, broke in from 6,000 to 11,000 hours. These experiments seem to show that a statical load of 60 per cent. of the immediate breaking weight is not safe. When broken immediately, the ultimate deflection was about 1·8 inch; with 350 lbs. it was 2·3 inches; with 300 lbs., 3·0 inches; and with 250 lbs., 2·5 inches. Hence the deflection is greater with a prolonged load. In Mr. Kidder's experiments on dry spruce beams $1\frac{1}{2}$ inch square, the deflection increased with time, even when as small as $\frac{1}{15}$th of the immediate breaking weight. He concluded that one-half of the immediate breaking weight could not be permanently supported.

268. *Strength of Various Colonial Timbers.*[1]—During the past three years a series of logs have been forwarded to the Imperial Institute by different colonies. At the request of Sir F. Abel, F.R.S., these have been tested for strength by the author, and the results have been published in the *Journal of the Imperial Institute*. A short abstract of the results is given here.

Density Tests.—These were made on blocks prepared for compression tests, and they were from $2 \times 2 \times 6$ ins. to $3 \times 3 \times 8$ ins. Usually the density was determined by displacing water, but in some cases by measuring the block and weighing.

Wetness Tests.—These were made on drillings from the transverse test bars taken immediately after the test. The shavings were weighed at once, and then again after about 10 hours' drying in a water oven kept at 180° to 212° F.

[1] The description of these tests has been given in detail in various numbers of the *Journal of the Imperial Institute*, 1895–98.

The moisture percentage is reckoned on the weight of the dry wood.

Bending Tests.—For the bending tests the bars were generally from 2 ins. × 2 ins. to 3 ins. × 3 ins., and from 30 to 40 ins. span. All the bars were supported at the ends and loaded in the middle, and the deflections were carefully taken for every 500 lbs. load. Let w = breaking load at centre, l = span in ins., b = breadth, and d = depth of test bar in inches. Then—

$$f = (1{\cdot}5\ \mathrm{w}l)/(bd^2)$$

is the coefficient of bending strength.

The deflections of timber are never quite regular, and, strictly speaking, timber has no true elastic limit. It is not a homogeneous material, and different parts give way differently. But the deflections are nearly constant for equal increments of load for a certain range of stress. Let δ be the mean deflection for this range of loading, corresponding to an increment w of load. Then the coefficient of elasticity is

$$\mathrm{E} = (0{\cdot}25\ wl^3)/(bd^3\ \delta).$$

For the range of stress taken in calculating E, the timber may be said to be practically elastic. The elastic limit is in a rough practical sense the greatest stress up to which the deflections for equal increments of load were approximately constant.

Crushing Tests.—The blocks for crushing were rectangular blocks, sometimes as small as 2 × 2 × 6 ins., but more commonly 3 × 3 × 8 ins. Most of the blocks gave way by shearing, but some by vertical splitting.

Shearing Tests.—The bars for shearing were sheared at a single section of approximately 4 sq. ins. area along the fibres.

The shearing shackle is shown in fig. 111.

—	Name of timber	Locality	Heaviness, lbs. per c. ft.	Moisture per cent., reckoned on dry wood	Coefficient of elasticity from bending test, tons per sq. in.	Range of stress for coefficient of elasticity, lbs. per sq. in.	Coefficient of bending strength, tons per sq. in.	Crushing strength, tons per sq. in.	Shearing strength along the fibres, tons per sq. in.
1	White ironwood	Natal	60·37	—	772	0–9,800	8·56	4·33	—
2	Red milkwood	,,	52·40	—	876	0–11,200	9·52	—	—
3	White pear wood	,,	42·84	—	635	0–5,315	6·95	3·04	—
4	Sneeze wood	,,	61·11	—	782	0–12,180	8·62	5·96	—
5	Black ironwood	,,	64·68	—	896	0–7,476	7·84	4·79	—
6	Wallah wood	Brit. Guiana	52·06	—	1,171	0–11,180	8·13	4·28	·424
7	Mora wood	,,	64·76	—	1,465	0–9,350	9·42	5·34	·655
8	Albizzia	India	64·48	—	987	0–6,107	6·11	3·53	·353
9	Locust wood	Montserrat	58·97	—	746	0–8,600	7·67	5·17	·585
10	Saffron wood	Cape Colony	47·50	—	510	0–4,915	4·41	3·18	—
11	Kafir plum	,,	45·73	—	738	0–7,165	5·85	2·94	—
12	Olive wood	,,	68·95	—	669	0–6,000	6·65	3·90	·800
13	Red cedar	Montserrat	31·08	—	371	0–4,100	3·02	1·98	·362
14	Spanish oak	St. Vincent	49·14	—	873	0–7,290	5·78	—	·550
15	Flat crown	Natal	38·67	—	610	0–9,005	6·06	3·03	·644
16	Kauri	Auckland, N.Z.	37·39	—	470	0–3,800	2·16	2·03	—
17	Stringy bark (*Eucalyptus obliqua*)	Tasmania	66·40	47·9	1,202	0–7,560	4·72	2·91	·476
18	Blackwood (*Acacia melanoxylon*)	,,	63·50	46·0	1,064	0–8,400	5·45	3·24	·687
19	Myrtle (*Fagus cunninghami*)	,,	52·45	28·1	842	0–7,040	4·06	2·58	·557
20	Crows-ash	Queensland	77·82	28·0	960	0–10,110	7·03	4·54	·620
21	Iron bark	,,	70·46	28·4	1,056	0–12,010	7·05	4·00	·681
22	Spotted gum	,,	71·70	41·5	927	0–8,552	6·42	3·78	·431
23	Blood wood	,,	72·60	45·8	1,023	0–12,550	7·57	4·48	·615
24	Blue gum	,,	61·13	40·6	371	0–5,103	3·57	2·27	·510
25	Black butt	,,	59·36	32·5	1,152	0–8,252	5·79	3·75	·360
26	Fallow wood	,,	70·50	41·6	896	0–8,890	5·48	4·02	·618
27	Satin wood	Jamaica	55·99	11·8	780	0–3,940	—	4·34	·585
28	Satin wood	,,	61·15	12·5	775	0–11,560	6·62	4·28	·305
29	Cashaw wood	,,	61·26	25·6	874	0–10,460	6·43	3·76	·851
30	Lignum vitæ	,,	76·47	13·6	498	0–3,619	4·88	3·41	·447
31	Lignum vitæ	,,	74·86	11·4	508	0–1,057	—	4·33	1·246
32	Rosewood	,,	74·45	7·7	986	0–9,662	6·72	5·71	·351
33	Greenheart	Brit. Guiana	74·94	29·7	1,092	0–6,139	8·61	3·58	·291
34	Bullet wood	,,	80·97	21·3	1,097	0–4,079	8·58	4·77	·494
35	Bastard cabbage	Jamaica	60·41	59·6	639	0–5,274	5·44	2·99	·450
36	Yoke wood	,,	70·48	60·1	286	0–3,346	3·04	2·09	·317
37	Spanish elm	,,	47·69	40·3	553	0–4,392	2·73	2·16	·428
38	Calabash	,,	54·69	76·4	230	0–2,706	2·62	1·69	·358
39	Naseberry bullet	,,	74·27	41·9	1,080	0–6,882	9·16	4·31	·503
40	Red or cherry bullet	,,	71·26	55·2	958	0–7,714	6·12	3·56	·503
41	Mountain mahoe	,,	33·46	34·7	363	0–3,860	3·24	1·97	·336
42	Mammee sapota	,,	59·16	31·9	763	0–8,615	6·95	3·57	·555
43	Mammee	,,	61·29	37·9	857	0–11,080	7·43	2·23	·362
44	Prune	,,	66·23	51·7	919	0–6,750	6·85	3·43	·739
45	Mountain guava	,,	65·04	32·6	820	0–10,300	8·29	3·83	·386
46	Hog-gum	,,	50·21	41·5	728	0–6,270	5·14	2·91	·462
47	Hog-meat	,,	73·82	29·0	638	0–8,861	5·69	3·65	·470

—	Name of timber	Locality	Heaviness, lbs. per c. ft.	Moisture per cent., reckoned on dry wood	Coefficient of elasticity from bending test, tons per sq. in.	Range of stress for coefficient of elasticity, lbs. per sq. in.	Coefficient of bending strength, tons per sq. in.	Crushing strength, tons per sq. in.	Shearing strength along the fibres, tons per sq. in.
48	Blue mountain yacca	Jamaica	38·59	18·1	456	0–6,442	4·31	2·49	·486
49	St. Ann's yacca	,,	44·67	56·6	596	0–6,335	5·25	2·52	·346
50	Yellow sanders	,,	57·29	33·8	721	0–6,430	4·51	4·02	·368
51	Prickly yellow	,,	60·66	33·7	499	0–4,179	2·70	1·77	·418
52	Wannika	,,	65·34	25·6	695	0–5,211	2·93	2·77	·485
53	Seaside grape	,,	65·34	59·8	637	0–2,573	4·13	2·52	·428
54	Seaside mahoe	,,	48·31	50·8	370	0–3,489	4·45	2·21	—
55	St. Ann's yacca	,,	46·95	33·1	548	0–4,599	5·13	2·55	·348
56	Pyiuma (*Lagerstræmia flos-reginæ*)	India	41·77	13·8	544	0–2,250	5·22	2·76	·337
57	Greenheart (*Nectandra rodiæi*)	Brit. Guiana	76·54	56·9	1,286	0–6,140	8·97	5·17	·435
58	Souari (*Caryocar tomentosum*)	,,	69·36	62·6	1,050	0–5,515	5·87	3·05	·472
59	Light brown cironballi (*Nectandra*)	,,	41·18	25·5	694	0–4,200	5·98	1·89	·216
60	Kabucalli (*Goupia tomentosa*)	,,	74·43	52·6	672	0–5,700	4·26	3·40	·471
61	Mora (*Mora excelsa*)	,,	72·31	45·8	1,068	0–6,600	6·87	3·14	·456
62	Locust (*Hymenæa courbaril*)	,,	58·58	20·2	1,018	0–6,344	8·13	5·41	·490
63	Simarupa (*Simarupa officinalis*)	,,	28·35	16·8	473	0–4,940	3·36	1·78	·224
64	Hackia (*Siderodendron triflorum*)	,,	65·81	47·2	1,027	0–5,900	6·72	4·85	·457
65	Crabwood (*Carapa guianensis*)	,,	46·25	—	—	—	—	3·29	·433
66	Euriballi	,,	49·36	—	—	—	—	4·04	·428
67	Santa Maria (*Calophyllum calaba*)	Honduras	52·95	48·0	790	0–6,918	5·14	2·60	·215
68	Turtle bone	,,	64·95	43·0	464	0–2,979	4·43	2·22	·480
69	Billet wood	,,	70·86	33·7	481	0–5,000	3·40	2·40	·547
70	Salen wood	,,	37·88	22·4	602	0–4,490	4·51	1·82	·299
71	Purple heart	,,	63·66	35·1	946	0–8,170	5·93	3·11	·376
72	Black maya	,,	64·76	39·1	933	0–4,470	5·39	2·77	·386
73	Dogwood (*Piscidia*)	,,	56·89	52·0	506	0–5,580	3·74	2·03	·387
74	Cabbage bark (*Andira inermis*)	,,	56·87	42·8	563	0–2,250	2·01	1·98	·320
75	Redwood	,,	52·47	52·8	459	0–6,600	3·81	2·09	·290
76	Billy Web	,,	61·45	24·5	1,178	0–13,600	9·10	4·50	·529
77	Locust wood	,,	49·89	32·1	549	0–4,620	4·54	2·23	·560
78	Granadilla	,,	60·49	25·9	565	0–6,760	4·74	4·16	·429
79	John Crow wood	,,	60·09	43·8	408	0–3,740	3·75	2·96	·366
80	Habing	,,	58·39	33·0	350	0–5,560	3·97	3·02	·370
81	Black poison wood	,,	65·72	54·3	605	0–9,000	4·52	2·63	·326
82	Sapu	Ceylon	41·41	—	502	0–7,815	3·45	1·57	·336
83	Panah ka	,,	54·86	—	658	0–12,960	5·78	2·77	·333
84	Gurukina	,,	62·62	—	657	0–8,736	3·90	2·41	·423
85	Vuinauku	,,	40·41	—	430	0–9,500	4·25	1·93	·217
86	Satin wood	,,	64·32	—	699	0–13,780	6·15	3·37	·850
87	Milla	,,	60·92	—	721	0–14,760	6·59	3·12	·448

—	Name of timber	Locality	Heaviness, lbs. per c. ft.	Moisture per cent., reckoned on dry wood	Coefficient of elasticity from bending test, tons per sq. in.	Range of stress for coefficient of elasticity, lbs. per sq. in.	Coefficient of bending strength, tons per sq. in.	Crushing strength, tons per sq. in.	Shearing strength along the fibres, tons per sq. in.
E	Sneezewood	CapeColony. East Conser.	67·4	—	984	0–13,622	7·22	5·37	·490
F	Common yellow wood	,,	34·1	—	645	0–6,265	4·03	2·56	·290
G	Upright or real yellow wood	,,	33·6	—	435	0–6,046	4·04	2·23	·264
H	Assegai	,,	60·2	—	1,106	0–11,170	7·30	3·75	·621
I	Black ironwood	,,	54·6	—	793	0–7,145	5·46	3·37	·528
K	White pear	,,	61·3	—	776	0–6,019	6·42	3·13	·740
L	Saffraan	,,	56·0	—	523	0–6,050	5·40	2·77	·559
A	Stone pine	CapeColony. WestConser.	35·3	—	425	0–3,842	4·58	2·22	·368
B	Blue gum	,,	51·1	—	726	0–8,752	6·27	3·80	·454
C	Cluster pine	,,	36·1	—	714	0–7,437	5·39	2·27	·490
D	Clanwilliam cedar	,,	38·5	—	392	0–4,723	3·69	2·46	·226
M	Saffraan	CapeColony. Mid. Conser.	55·7	—	729	0–9,722	7·21	3·55	·604
N	Ironwood	,,	63·2	—	1,095	0–16,790	8·85	4·63	·448
O	Kersehout	,,	66·4	—	585	0–5,139	5·05	3·09	·660
P	Vlier	,,	44·0	—	733	0–10,270	6·62	3·28	·462
Q	Keur	,,	44·2	—	661	0–8,535	5·68	2·84	·606
R	Assegai	,,	57·1	—	783	0–10,080	6·75	3·92	·572
S	Upright or real yellow wood	,,	38·7	—	650	0–7,504	5·02	3·16	·260
T	Red els	,,	46·4	—	787	0–7,610	5·40	2·99	·490
V	Cape beech or Beukenhout	,,	46·1	—	733	0–8,072	4·96	2·75	·504
W	Common yellow wood	,,	30·2	—	418	0–5,340	3·70	2·22	·255
X	Stinkwood or Cape laurel	,,	50·8	—	839	0–13,820	7·51	4·06	·584
Y	White els	,,	33·1	—	334	0–4,985	3·12	2·67	·291
Z	Hard pear	,,	54·3	—	534	0–2,987	2·67	3·48	·608
ZZ	White pear	,,	49·0	—	766	0–8,034	6·78	3·64	·527

In figs. 190 and 191 the results on bending and crushing down to number 87 have been plotted. The strengths are proportional to the weight of the timber in a general sense. For each timber the weight per cubic foot has been taken as abscissa and the strength as ordinate. Each point is marked with the number in the preceding table corresponding to the results plotted. Timbers for which the plotted point lies relatively low are poor timbers; those for which the plotted point is relatively high are good timbers.

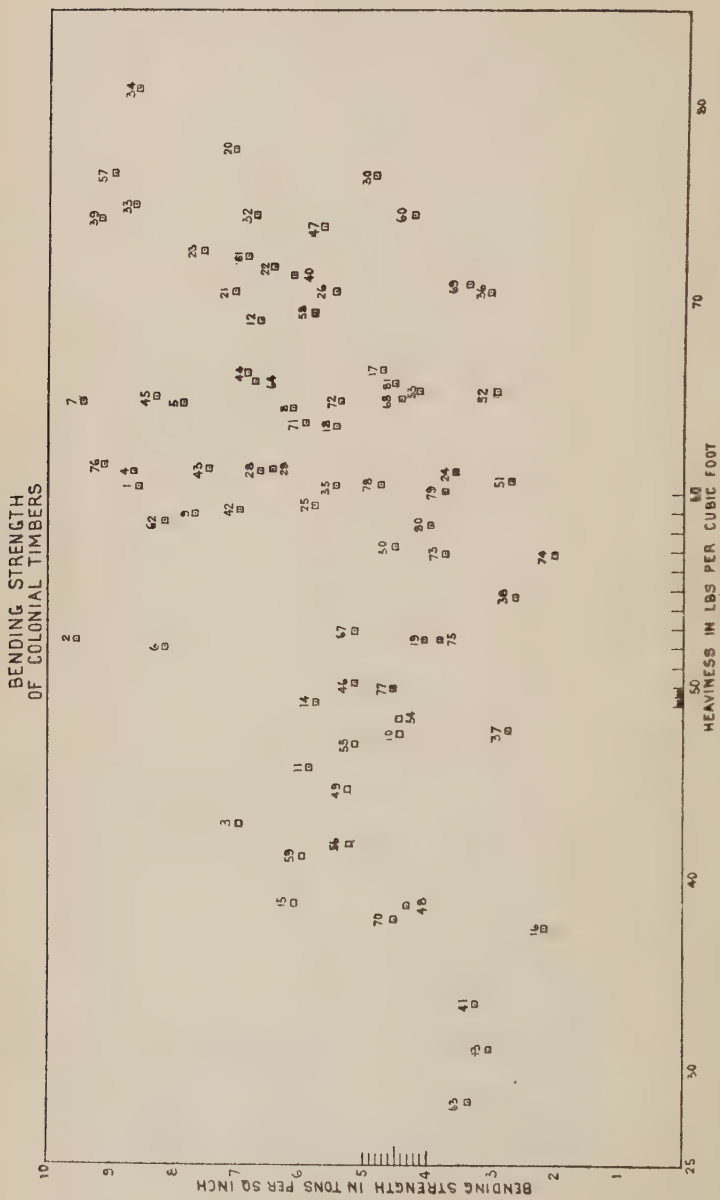

BENDING STRENGTH
OF COLONIAL TIMBERS
BENDING STRENGTH IN TONS PER SQ INCH
HEAVINESS IN LBS PER CUBIC FOOT

FIG. 190.

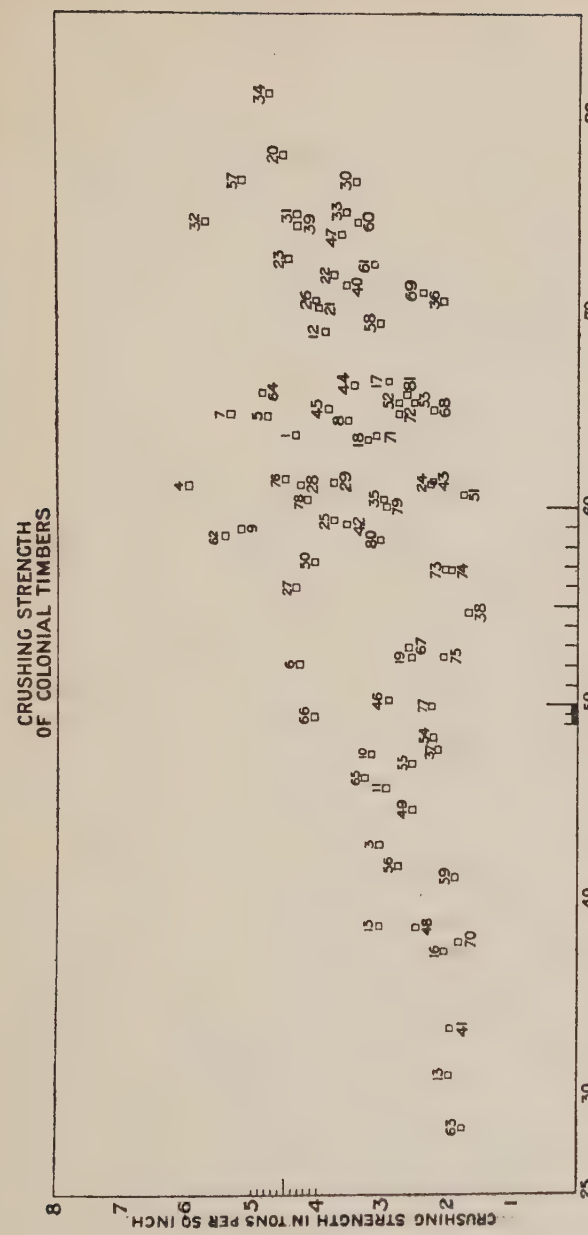

CRUSHING STRENGTH
OF COLONIAL TIMBERS
CRUSHING STRENGTH IN TONS PER SQ INCH
HEAVINESS IN LBS PER CUBIC FOOT.
8
7
6
5
4
3
2
1
25
30
40
50
60
70
80

FIG. 191.

CHAPTER XVIII

STONE AND BRICK

269. Building stone is derived from rocks of widely different origin and very various age. The rocks may be distinguished into volcanic or plutonic rocks consolidated from igneous fusion, and stratified rocks deposited under water. The former are crystalline in the granites, less obviously crystalline in the traps, and glassy in other cases. The stratified rocks, which show more or less distinctly lamination or bedding, are sometimes aggregates of detritus derived from denudation of land surfaces, cemented by subsequent infiltration. Sometimes they are of organic origin, and consist largely of siliceous or calcareous skeletons. In some originally stratified rocks a slaty cleavage has been developed by pressure, which is more conspicuous than the original bedding.

The value of stone for building depends on its strength, its durability, and the facility with which it can be worked. The durability depends partly on its hardness and chemical composition, but also largely on its power of resisting the absorption of water.

Granite consists normally of quartz, colourless and transparent; felspar, opaque, red, yellow, or grey, giving the prevailing tint to the rock; and mica. Hornblende and talc are sometimes associated with or replace the mica. Granite is an extremely valuable building stone. It is heavy, strong, non-absorbent, and capable of taking a fine polish. On the other hand, it stands fire badly, and is difficult to work. The hornblendic varieties have great resistance to abrasion. Inferior granites sometimes decay, either by decomposition of the felspar, or by surface disintegration by frost.

Trap, Greenstone, and Basalt have some of the qualities of granite. They are compact crystalline rocks, composed of felspar, hornblende, and augite. They are strong, but difficult to dress.

Clayslate, composed of quartz and mica, is sometimes a very compact rock, yielding a fine-grained and strong building stone. Sometimes the slaty cleavage is so developed that it yields slabs and roofing slates.

Sandstones are stratified rocks, composed largely of quartz grains, with a siliceous, clayey, or calcareous cement. The fineness of grain varies greatly. In some sandstones the cement is nearly pure silica, and these are strong, durable, and non-absorbent. The best sandstones for building, in England, are obtained from the millstone grit and coal measures, and from the new and old red sandstone formations.

Limestones are of very various texture and quality. Marble is a nearly pure carbonate of lime, hard enough to take a polish. Granular and oolitic limestones consist of grains of carbonate of lime cemented by a calcareous or siliceous matrix. Some of these yield excellent, durable, and easily-worked building stone. Generally, however, limestones are softer, more absorbent, and less durable than sandstones. Shelly limestones consist of shells embedded in a more or less crystalline matrix, and some of these are useful as building stone.

Magnesian Limestones, or dolomites, consist of carbonates of lime and magnesia. When properly crystalline in structure they yield a good, easily dressed, and durable stone. Steatite, or silicate of magnesia, is valuable from its power of resisting fire.

270. *Strength of Stone.*—In most cases stone is used in compression. A block of stone at the base of a pier or in an arch ring is subject to a thrust due to the weight of the structure, and, as far as the condition can be secured, the thrust is normal to the faces of the block. Generally the pressure does not reach 10 tons per sq. ft., though in some lofty structures it reaches 20 to 30 tons, and possibly in some arch rings 40 or 50 tons, per sq. ft. Now the crushing resistance of stone, tested in small cubes, is seldom less than 250 tons, and often reaches 1,000 tons or more, per sq. ft. Hence it has been argued that the strength of stone is of little consequence, its lowest strength being in excess of what is required. It must be remembered, however, that small cubes of stones are selected specimens, more homogeneous and free from defect than large blocks. The cubical form is a stronger one than that of the blocks used in building, and single blocks are stronger than aggregates of blocks. Further, it is quite

impossible in any actual structure to secure a simple condition of crushing stress. Settlement, imperfect bedding, unequal compressibility of different blocks, and other causes, introduce unforeseen and incalculable straining actions. Hence, the real factor of safety is not nearly as great as the nominal one.

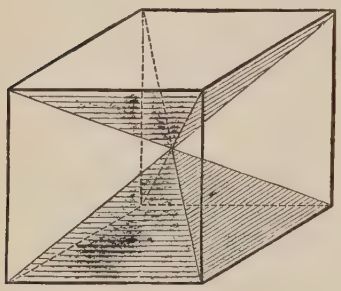


Fig. 192.

271. *Mode of Crushing in Rigid Materials.*—In ductile materials like wrought iron the mode of yielding to pressure is nearly the inverse of the mode of yielding to tension, and the two resistances are not widely different. But in cast iron and stone and other rigid materials, the tenacity of which is small compared with the resistance to crushing, the mode of

Fig. 193.

yielding is quite different. The stress on any oblique plane in a prism, subjected to a pressure p in the direction of its axis, may be resolved into a tangential component $p \sin \theta \cos \theta$,

and a normal component $p \cos^2 \theta$. On a plane making 45° with the axis, the intensity of the shearing stress is greatest, and equal to $\frac{1}{2} p$. Now small cylinders of cast iron frequently give way along a plane at about 45° with the direction of pressure, and Coulomb inferred that the action was then a simple shearing. But that this is not an exact view of the matter is proved, partly because the inclination of the plane of yielding to the axis often differs a good deal from 45°, partly because the intensity of the stress on the plane of yielding is usually greater than the shearing strength of the material when not in compression. Obviously, the normal component $p \cos^2 \theta$ is not without influence on the angle and intensity of stress at which the prism breaks. It produces a frictional resistance to sliding which balances part of the tangential stress.

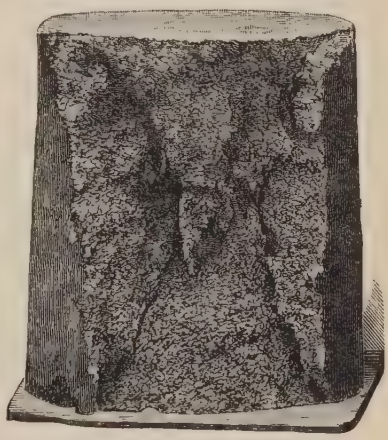


Fig. 194.

In a square prism there are four symmetrical planes similarly situated with respect to the axis. Hence such prisms frequently yield simultaneously at these four planes. Thus, a cube breaks into six similar and equal pyramids (fig. 192; see also fig. 195). With a rectangular base a prism breaks similarly, but the upper and lower pyramids are terminated by an edge instead of a point. A cylindrical prism shows, after fracture, two cones with the sides split off all round. In an even-grained material like sandstone these forms are often very regularly developed.

Fig. 193 shows a cube of cement concrete after fracture. Here the pyramidal form of fracture is pretty obvious, in spite of the irregularity of the material. The middle part, near the apex of the pyramids, is really loose and fissured. Fig. 194 exhibits a cylinder of cement mortar showing very distinctly the conical fracture.

When the height of the prisms is greater than their length of side, the two pyramids which stand on the surfaces

at which the pressure is applied are often of unequal height.

272. *Preparation of Specimens for Crushing.*—The specimens required for crushing may be obtained by sawing, or by dressing with hammer and chisel. It is of the greatest importance that the surfaces at which the crushing pressure acts should be plane and parallel. To secure this the surfaces may be ground smooth with emery on a plate of stone or metal. As this is troublesome, especially when dealing with bricks, concrete blocks, and other rough material, the author has adopted a plan which is simpler, and satisfactory. When the surfaces are approximately right, they are covered with a thin layer of Parian cement or plaster of Paris, which can be easily strickled so as to be plane. This thin layer does not crush, even under the heavy pressures required, and it does not yield or flow. It is for all practical purposes a part of the block. Plaster faces were used by the author on the concrete blocks from Vyrnwy in 1882, the tests of which are given in a later table. Since then this method of preparing compression blocks has been generally adopted.

To avoid the trouble of getting parallel plane surfaces, it has been common to make crushing experiments with a layer of pinewood, or lead, or other weak material interposed between the block to be crushed and the cast-iron crossheads of the testing-machine. The idea has been that the wood or lead distributed the pressure over the surface, and virtually annulled the inequalities of surface. This, however, can be shown to be erroneous. Any weak material may greatly alter the crushing pressure, and falsify the result of the experiment. The block to be crushed should be placed directly between the parallel metal surfaces by which the pressure is applied. The only thing which may be used between is a sheet of hard millboard. This is nearly incompressible, and does not flow under the crushing pressure. It does no harm, and it is doubtful if it does any good. To neutralise, as far as possible, the effect of any want of parallelism of the surfaces of the block and machine, a spherical joint should be used.

273. *Diminution of the Crushing Resistance of Stone when bedded on Lead.*[1]—It was common, in experiments on crushing,

[1] Resistance of stone to crushing as affected by the material on which it is bedded. Unwin, *Brit. Association Report*, 1887, p. 879. The amount of reduction probably depends on the thickness of the lead. It is greater the stronger the stone.

to bed the test specimens of rigid materials, like stone, on lead plates, with an idea of securing uniform distribution of pressure on the faces at which the crushing pressure is applied. The author has long had the opinion that to support blocks for crushing on a plastic support is wrong in principle. Hence, in experiments on the crushing of stone and of Portland cement and concrete, he adopted the plan of preparing the faces on which the crushing pressure acts with a thin layer of plaster. This can easily be worked to smooth and parallel surfaces, which receive the iron plates of the crushing shackles directly. To try what was the difference of the crushing strength of blocks supported in these two ways, two series of 4-inch cubes of Portland stone and Yorkshire grit were obtained of very uniform quality. The results of the tests are given below. The great reduction of strength when a thin plate of plastic material, like lead, is used on the faces to which the crushing pressure is applied is interesting both practically and scientifically. It will be seen that the crushing pressure of blocks between lead plates is in one case only three-fifths, and in another only three-sevenths, of that of blocks prepared with plaster and crushed between millboard. One block was cemented carefully between two

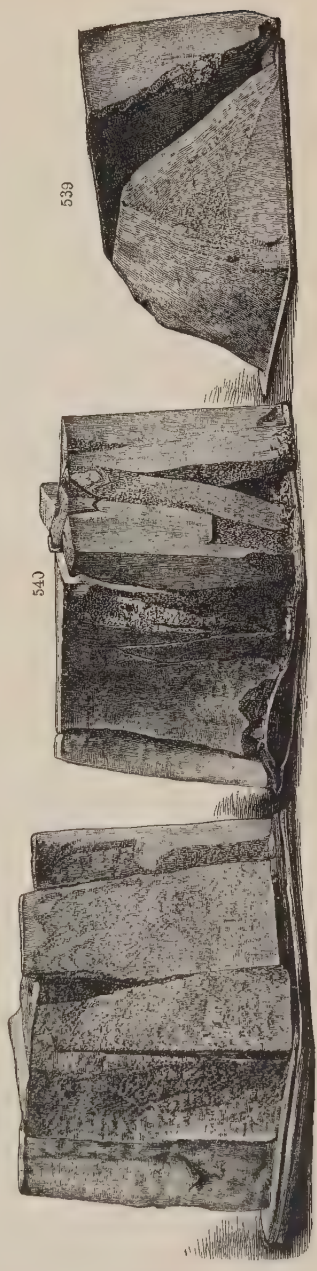


FIG. 195.

rigid iron plates with parallel surfaces, and this carried a little more load than the block prepared with plaster and crushed between loose millboards. An examination of the mode of fracture of the blocks shows why the lead has so dangerous an effect on the strength. The blocks crushed between millboards sheared approximately at 45°, forming regular pyramids; but the blocks crushed between lead broke up into a number of vertical prisms. The lead, flowing under the crushing pressure, produced by friction a tension in the block at right angles to the crushing pressure, and this, added to the lateral extension, tore the block in pieces, completely altering the angle of fracture. The pressure of fluidity of lead is from 1½ to 3 tons per sq. in., and these pressures were exceeded in the crushing experiments.

Crushing of Stone Blocks, 4-inch Cubes (Unwin)

Description of stone	Crushing load in tons	Stress in tons per sq. ft.	Remarks
Portland :			
535	57·665	516·38	Between two millboards on each face
536	52·600	469·87	One lead plate on each face
538	45·65	408·8	One plate of lead on each face, ⅛ inch smaller than face all round
537	33·50	299·95	Three plates of lead on each face
Yorkshire grit :			
539	79·72	712·08	Between two millboards on each face
542	80·05	716·86	Cemented between two strong iron plates with plaster of Paris
540	56·20	504·43	One lead plate on each face
541	35·90	322·27	Three plates of lead on each face

The lead plates were 0·085 inch thick.

The result seems important, because it is still a common practice to use lead, or deal, or some other plastic or compressible material, in crushing experiments, and sometimes in structures, and it is not generally known that this has the effect of diminishing the crushing resistance.

Fig. 195 shows three of the blocks of the Yorkshire grit

series after crushing. Block 539, crushed between millboards, has crushed in the normal way, a central wedge being formed, and the sides shearing on the four faces of the wedge. But in the two other blocks, supported on lead, the shearing angle is completely altered by the horizontal tension induced by the flow of the lead. The blocks are broken into a series of prisms or wedges, the dividing planes being nearly vertical.

In a note in the *Trans. Am. Soc. of Civil Engineers*, 1872, p. 192, it is mentioned that the Commission of 1851, on the Selection of Stone for the Capitol at Washington, discovered the fact that the crushing stress of stone was reduced to about one-half, if pieces of lead were interposed between the stone and the steel faces of the shackles.

274. *Influence of the Form of the Test Piece on the Crushing Strength.*—Building stone is most commonly tested in cubes, and cubes of 4 inches length of side are convenient. For some of the stronger stones, it may be necessary to use cubes of 2 to 3 inches side in many testing-machines. Portland cement is often tested in cubes of 4 inches length of side. For cement mortar the author has used cylinders of 7 inches diameter and 10 inches height. Irregular artificial material like cement concrete is best tested in the largest practical blocks. Cubes of 7 to 10 inches length of side are convenient.

It will be obvious, from the account given of the way in which materials of this kind crush, that knowledge of the crushing strength of different forms and sizes of specimen is purely experimental. The first attempt to examine precisely the law of crushing strength of such materials were made by Rondelet,[1] Vicat,[2] and Hodgkinson. Recently, Bauschinger has made a more complete investigation.[3]

For test blocks of geometrically similar form, all experiments show that the crushing strength varies at the area of the surface on which the crushing pressure acts. Thus, Rondelet experimented on cubes of 1·2, 1·6, 2·0, and 2·4 inches length of side, of three different kinds of stone. The crushing pressures per unit of area were, in tons per sq. ft.:

First series . .	246	243	243	248
Second series . .	107	104	114	112
Third series . .	50	50	50	51

[1] *L'Art de Bâtir*, t. iv. [2] *Annales des Ponts et Chaussées.* 1833.
[3] *Mitth. aus dem Mech. Tech. Laboratorium.* 1876.

More generally this law may be stated thus: The strength of geometrically similar test pieces varies as the square of homologous sides.

The variation of the crushing strength of prisms with the form of the cross-section is less obvious. Hodgkinson concluded that the form of the cross-section had little influence. But Rondelet found, with prisms of circular, square, and triangular bases of equal area, that the strengths were proportional to 1 : 0·93 : 0·86; and for prisms on a square base and rectangular base, with sides as 1 : 2, of equal area, the strengths were as 1 : 0·95. These numbers are nearly in the reciprocal ratio of the square roots of the circumferences.

When cubes are used, placed on each other, the strength diminishes with the number of cubes. Thus, for columns of one, two, and three cubes of 2 inches length of side, Rondelet found the strengths in two series of experiments to be 1 : 0·61 : 0·54, and 1 : 0·80 : 0·75.

The strength in prisms of similar base but different heights diminishes as the height is greater, and that for heights within the limit at which any bending occurs.

Lastly, a single block is always stronger than a compound block of the same form made of separate blocks without cement. Thus, a cube made up of four blocks of gypsum had a strength only 0·78 of that of a single block of the same size. A block of eight small cubes had a strength of 0·84 of that of a single cube of the same size.

Bauschinger has found that all these results can be expressed by the relation—

$$f = \left(\frac{4\sqrt{\text{A}}}{\text{C}}\right)^{\frac{1}{2}} \left(\lambda + \nu\frac{\sqrt{\text{A}}}{h}\right) \quad . \quad . \quad . \quad (1),$$

where A is the area of section of prism, C its circumference, h height of prism, f strength per unit of section, and λ and ν are constants for each material.[1]

It gives at once the law that prisms and cylinders of geometrically similar form have the same strength. Also, that in prisms of the same height and sectional area the strength varies inversely as the square root of the circumference. Thus, prisms of circular, square, and triangular base, of the same height, should have strengths varying as

[1] See also a later paper by Martens. *Mitth. aus den Versuchsanstalten zu Berlin*, 1896.

1 : 0·94 : 0·88. For square prisms of different heights the equation becomes—

$$f = \lambda + \nu \frac{s}{h} \quad . \quad . \quad . \quad . \quad . \quad (2),$$

where s is the side of the square. According to Bauschinger, this equation is valid up to values of $h = 4\,s$ or $5\,s$. A series of experiments on square and rectangular prisms of different heights, varying from 0·6 to 12 inches, of fine Swiss sandstone, gave the following values of the constant (f, in tons per sq. in.)—

$$\lambda = 239{\cdot}5 \qquad \nu = 292{\cdot}5,$$

when the axis of the prism was parallel to the layers. In another series of experiments on prisms of the same sandstone, crushed perpendicular to the layers, the height, however, not exceeding that of the cube,

$$\lambda = 283{\cdot}5 \qquad \nu = 316.$$

A third series of tests on rectangular and square prisms of Perlmooser Portland cement, hardened ninety days, gave—

$$\lambda = 139 \qquad \nu = 98{\cdot}6.$$

Tests were made on rectangular and cylindrical prisms of about 4 inches diameter or length of side and very different heights, cut out of fine-grained Bunter sandstone, and crushed parallel to the layers. These gave—

For prisms . .	$\lambda = 317$	$\nu = 111$
„ cylinders .	„ 337	„ 105
Mean . . .	„ 327	„ 107·5.

A series of tests with square and rectangular prisms of different heights, having sides with the ratios 1 : 2, 3 : 4, and 1 : 1, also of a fine-grained sandstone, gave—

$$\lambda = 356{\cdot}5 \qquad \nu = 97.$$

Bauschinger shows that the agreement of the equation with the results is throughout satisfactory.

Bauschinger made a further research on the crushing strength of cubes when on one surface the crushing load was confined to a portion of the area. Suppose fig. 196 is the plan of a cube, and that either by bevelling the edges, or by using a small steel pressure-plate, the load is confined to the area of the small rectangle. If o is the centre of the rectangle, and

$$o\,b = e_1;\ o\,d = e_2;\ o\,a = e';\ o\,c = e'',$$

f = crushing pressure per unit of area when pressure is uniform on whole face of cube; f_1 = crushing pressure per unit of area of pressure-plate.

Then,
$$f_1 = f\sqrt[3]{\frac{e_1\,e_2}{e'\,e''}}.$$

If A and a are the areas of the surface of the cube and pressure-plate, then, when the pressure-plate is central—

$$f_1 = f\sqrt{\frac{A}{a}}.$$

If two equal pressure-plates on both faces of the cube are used, then the strength becomes that of the prism of material between the pressure-plates, and is nearly independent of the amount of material surrounding this prism. It is easy to see, therefore, how much a block of stone may be weakened by imperfect bedding.[1]

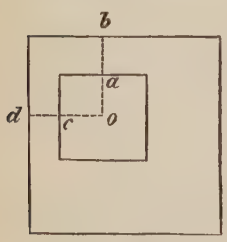


Fig. 196.

275. *Determination of the Porosity of Stone.*—Specimens for this purpose should be cubes, and should be well dried. The stone should be brushed, weighed, and then immersed in water. The stone is allowed to remain under water till saturated. It will become nearly saturated in twenty-four hours, but it may, for certainty, be left for five days. It is then taken out, carefully dried on the surface, and weighed.

[1] A similar research by M. Flamant is given in *Ann. des Ponts et Chaussées*, vol. xiv., and *Proc. Inst. C.E.* vol. xci.

The gain of weight is estimated in per cent. of gross weight. Sometimes the process is hastened by removing the air pressure by an air-pump and allowing it to return.[1] For

—	Per cent. of water absorbed	No of hours' immersion	Authority
Granites (various)	0·42–1·2	125	Böhme
Syenite	0·50	125	,,
Porphyry	0·4–2·8	125	,,
Granites	0·2–3·0	24	Wray
Trachyte	2·0–4·5	125	Böhme
Slate	·54–·70	125	,,
Roofing slate	0·5	24	Wray
Sandstones (various)	0·7–8·2	125	Böhme
Coal-measure sandstones	1·0–7·0	24	Wray
Old red sandstone	1·6–3·8	24	,,
New red sandstone	6·0–10·0	24	,,
Lias sandstones	3·0–8·0	24	,,
Craigleith	8·0	24	Royal Com.
Kenton	9·9	24	,,
Mansfield	10·4	24	,,
,,	2·6–4·8	24	Wray
Limestones (various)	0·31–6·4	125	Böhme
Portland	13·5	24	Royal Com.
Ancaster	16·6	24	,,
Box ground (Bath)	17·0	24	,,
Ketton	15·1	24	,,
Chilmark	8·6	24	,,
Roche Abbey	17·2	24	,,
Oolithic limestones	4·0–12·0	24	Wray
Shelly limestones (Purbeck)	4·0–2·0	24	,,
Kent rag	0·5	24	,,
Dolomite	1·5	125	Böhme
Magnesian limestone	3·5	24	Wray

strictly comparable results the specimens should be of the same volume and surface.

The following table gives the density and absorption of water of a series of 3-inch cubes of English stone. The blocks were weighed dry and then immersed in water for from seven to fifteen days. The weighings were carefully made for the author by Mr. H. M. Martin:

[1] Hatfield. *Trans. Am. Soc. of Civil Engineers*, 1872, p. 145.

Material	Density	Per cent. of water absorbed
Aberdeen granite, red	2·62	0·70
„ „ grey	2·68	0·81
Clayslate	2·76	0·31
„	2·76	0·23
SANDSTONES:		
Red Grinsell	2·16	5·49
White Grinsell	2·15	6·89
Scotgate Head (coal measure)	2·39	3·43
Corse Hill (new red)	2·29	5·05
Robin Hood (coal measure)	2·32	5·41
Hollington	2·19	6·42
Red Mansfield	2·35	4·44
White „	2·30	5·55
Red „	2·37	4·67
Flag-rock Grinsell	2·21	5·08
Red Alton (new road)	2·16	7·43
Derbyshire grit	2·18	6·06
Billstone	2·21	6·03
Howley Park	2·33	4·28
Attleborough	2·02	9·52
Hansworth	2·32	3·84
Duston (ironstone)	2·12	10·10
Ispatria	2·17	8·07
Sydanape	2·16	6·06
Kenilworth	2·06	9·11
LIMESTONES:		
White Portland	2·31	8·64
Portland	2·31	5·23
Brown Portland	2·27	6·22
Ancaster	2·15	8·52
Ketton	2·21	9·00
Stoke ground	2·17	8·90
Corsham Down	2·19	9·49
Westwood ground	2·01	12·75
Caen	1·96	12·56
Box ground	1·88	10·10
Church Anson	2·39	6·29
Doulting	2·19	7·99

Resistance to Frost.—The power of resisting frost can be inferred to some extent from the porosity. It is better, however, to saturate a stone with water and then freeze it, repeating the operation ten or more times. The percentage loss of weight is the measure of the injury done by frost. Brard's test is to immerse the stone for half an hour in a boiling saturated solution of sulphate of soda, and then hang it up for the absorbed salt to crystallise. The process is repeated daily for a week. It is a test of doubtful value.

Resistance to Wear.—The only method of satisfactorily testing the resistance of stone to wear is one devised by Bauschinger. A block of the stone, with a face 4×4 inches, is placed on a horizontally-revolving cast-iron plate at a radius of 18 inches. The conditions are found to be most constant when the block is loaded with 66 to 68 lbs. Emery is regularly supplied between the block and plate and cleaned off. The best rate of supply is twenty grams for each ten turns.

276. *Coefficient of Elasticity for Stone.*—The measurement of the compressions and extensions of stone is difficult, partly from the limitation of size of specimen, partly from the smallness of the deformations, partly from the difficulty of securing uniform distribution of stress. Professor Bauschinger appears to have overcome these difficulties[1] by the use of a modification of his mirror apparatus. Plottings to a very large scale of the stresses and deformations show that stone has no elastic limit. It takes permanent sets with very small loads, and the deformation does not increase at first proportionally to the loads and afterwards deviate from proportionality. For hard and dense stone the compressions and extensions are initially nearly proportional to the loads, and this remains so up to the breaking stress. For all others, especially for the weaker stones, the greatest departure from proportionality is for the smaller stresses. The greater the loads the more do the deformations approach to proportionality. For sandstone and the less hard granites, the compressions increase first more quickly than the loads and afterwards less rapidly. Hence, the stress-strain curve is at first convex and afterwards concave to the axis of loads. With repetition of loading the reversal of curvature gradually disappears.

In the later research in 1884, Bauschinger found for the hardest stone, and especially limestone, that the coefficient of elasticity was nearly constant, equal for tension and compression, and very large. For most other stone the coefficient of elasticity for tension diminishes with increasing loads. For pressure it sometimes increases with increasing loads, but for the weaker kinds it diminishes at first and then increases.

The stress-strain curves for tension and pressure pass into

[1] 'Ueber den Elasticitäts-Modul Baustein.' *Mitth. aus dem Mec. Tech. Laboratorium in München.* 1875. Extensometers for short gauge-lengths have now been devised which are satisfactory.

each other at the origin of co-ordinates without forming a cusp. But three cases are distinguishable: (1) If the coefficient of elasticity is nearly constant, the two curves for tension and pressure are nearly straight lines and inclined at nearly the same angle to the axis. (2) If the coefficient of elasticity diminishes with increasing loads in tension, the curve is concave to the axis of deformations. Then, (*a*) if the coefficient of elasticity for pressure increases from the beginning, or is nearly constant, the two curves form a regular line always concave in the same direction. But if (*b*) the coefficient of elasticity for pressure diminishes first and then increases, there is a point of contrary flexure at the origin of co-ordinates. Bauschinger is inclined to attribute this appearance to a disintegration of the test block in

COEFFICIENT OF ELASTICITY FOR STONE (BAUSCHINGER)

(Stresses and coefficients in tons per sq. ft.)

—	Bending		Tension		Pressure	
	Coefficient E	At a stress of	Coefficient E	At a stress of	Coefficient E	At a stress of
Granite (Metten)	192,000	2·2	216,000	2·6	264,000	2·7
„ „	125,000	86	54,000	35	244,000	460
„ (Passau)	104,000	4·1	202,000	0·6	113,000	1·4
„ „	40,000	73	28,000	33	199,000	410
Jura limestone (Kelheim)	315,000	1·5	175,000	1·3	310,000	1·8
„ „ „	58,500	27	71,500	12·5	185,000	172
Nummulite limestone	685,000	—	475,000	—	562,000	—
Bunter sandstone (Phalz)	27,400	1·1	26,600	0·6	60,200	0·9
„ „ „	17,000	28	11,900	6	172,000	207
„ „ (Würtzburg)	93,000	1·3	113,000	0·6	137,000	0·9
„ „ „	35,600	57	35,600	19	165,000	340
Molasse sandstone (Kempten)	173,000	1·1	116,000	2·2	153,000	1·4
„ „ „	43,000	56	29,100	31	240,000	530

dressing it by hammer and chisel. The author has obtained measurements of compression of stone similar to Bauschinger's. It seems possible that, in a granular substance like stone, the action of the pressure may be to bring the particles to a bearing, and that this may explain the decrease of the coefficient with increase of pressure.

The following table contains a few determinations of the coefficient of elasticity for compression made on some of the

blocks, the crushing strength of which is given in a later table:

COEFFICIENT OF ELASTICITY IN COMPRESSION (UNWIN)

Description of stone	Range of stress, tons per sq. ft.	Coefficient of elasticity, tons per sq. ft.
Welsh clay slate	80–400	275,000–650,000
Red sandstone (Runcorn)	9–22	85,700
" " " . . .	45–67	130,000
" " " . . .	112–135	149,000
" " " . . .	157–180	159,000
" " (Helsby) . . .	9–22	80,000
" " " . . .	45–67	106,000
" " " . . .	112–135	138,000
" " " . . .	157–180	134,000
Scotgate head (sandstone) . . .	83–325	143,500
Red Alton " . . .	0–154	53,500
" " . . .	154–231	61,500
Sydanape " . . .	0–82	45,200
" " . . .	82–165	90,000
" " . . .	165–247	100,200
Ketton (oolite)	0–77	192,000
" "	77–154	170,000
" "	154–231	157,000
Caen stone	78–157	61,000

277. *Bauschinger's First Research on the Strength of Stone* (*Mitth. aus dem Mech. Tech. Laboratorium in München*, 1874).—A few results will be selected from this paper as giving very conveniently the relative resistance to different kinds of straining action. The pressure tests were made on cubes with accurately ground surfaces, on which the cast-iron pressure-plates acted directly. For the shearing strength, three directions of shearing may be distinguished. The shearing plane may be normal to the laminæ, or beds, of the stone, and is then distinguished by the symbol $\perp$; or it may be in the plane of the beds, and is then indicated by the symbol $\parallel$. Bauschinger experimented in some cases in a third direction also; but these results are omitted. The same symbols apply to the bending experiments, and indicate the position of the plane of fracture.

Bauschinger's Second Research on the Strength of Bavarian Building Stones.[1]—In this series of tests parallelopipeds about 44 inches long and 10 inches × 8 inches square were used for bending tests, with a span of 40 inches. From one of the

[1] *Mitth. aus dem Mech. Tech. Laboratorium in München*, 1884.

	Pressure		Shear		Bending		Tension	
	Crushing stress, tons per sq. ft.	Direction of pressure	Shearing stress, tons per sq. ft.	Direction of shearing	Coefficient of bending strength, tons per sq. ft.	Direction of plane of fracture	Tenacity, tons per sq. ft.	Direction of pull
GRANITE:								
Coarse-grained grey (Selb, in Oberfranken)	725	⊥	34	⊥	—	—	—	—
" " " "	750	∥	46	∥	—	—	—	—
Black and white of mean coarseness (Hauzenberg)	930 [1]	⊥	100	⊥	192	⊥	40	∥
" " " "	940 [1]	∥	—	—	136	∥	30	⊥
Fine-grained yellow "	820	⊥	72	⊥	—	—	—	—
" " "	—	—	55	∥	—	—	—	—
Hard coarse-grained (St. Gotthard)	720	⊥	52	∥	84	∥	25	∥
" " "	810	∥	—	—	—	—	—	—
Yellow, rather fine-grained (Passau)	850	⊥	83	⊥	84	⊥	20	∥
" " "	850	∥	61	∥	89	∥	17	⊥
LIMESTONE AND DOLOMITE:								
White marble (Schlanders, in Tyrol)	820	⊥	—	—	—	—	—	—
Muschelkalk (Würtzburg)	400	—	53	—	63	—	25	—
" (Kronach)	1,460	⊥	54	⊥	—	—	—	—
" "	740	∥	43	∥	—	—	—	—
Limestone (Pappenheim)	1,000	⊥	61	⊥	—	—	—	—
" "	695	∥	40	∥	—	—	—	—
Dolomite "	1,190	⊥	64	⊥	165	⊥	25	∥
" "	1,080	∥	—	—	—	—	—	—
" (Königstein)	500	—	47	—	73	—	9	—
SANDSTONE:								
Bunter sandstone (Kronach)	300	⊥	20	⊥	—	—	—	—
" " "	174	∥	—	—	—	—	—	—
" " red and fine-grained (Wertheim)	720	⊥	61	⊥	105	⊥	14	∥
" " " " "	760	∥	—	—	—	—	—	—
Keuper sandstone, red and fine-grained (Wurtemburg)	580	⊥	68	⊥	—	—	—	—
" " " " "	420	∥	47	∥	—	—	—	—
" " white, fine-grained (Coburg)	290	⊥	14	⊥	27	⊥	4	∥
" " " " "	240	∥	12	∥	—	—	—	—
Molasse sandstone, blue, fine-grained (Allgau)	465	⊥	39	⊥	22	⊥	—	—
" " " " "	—	—	29	∥	—	—	—	—

broken pieces a prism was cut for pressure parallel to the laminæ. From the other, a test piece for tension parallel to the laminæ, and afterwards for shearing. Cubes were also obtained for pressure tests parallel and perpendicular to the laminæ. Some cubes were kept in water, and as opportunity served taken out and exposed to frost. After being frozen about twenty-five times, they were dried, and crushed in a direction parallel to the layers.

STRENGTH OF BAVARIAN BUILDING STONE (BAUSCHINGER)

(Stresses in tons per sq. ft.)

—	Coefficient of bending strength, ⊥ to bed	Tenacity, ∥ to bed	Crushing strength of prism, 1 : 1 : 2½	Crushing strength of cubes			Shearing strength	
				∥ to bed	∥ to bed after freezing	⊥ to bed	⊥ to bed	∥ to bed
Granite (Metten) . .	87	40	830	1,210	1,380	1,230	88	9
„ (Passau) . .	77	44	850	1,290	1,310	1,230	93	55
Jura limestone (Kelheim)	30	13·7	226	560	213	{210 / 460}	32	19
Bunter sandstone (Pfalz)	30	7	334	{286 / 455}	435	{435 / 525}	37	23
„ „ (Würtzburg)	63	40	710	970	780	835	63	35
Green sandstone (Kelheim)	10	6	177	277	260	302	22	21
Molasse sandstone (Kempten)	38	21	545	930	—	870	43	24
Molasse sandstone (Kempten)	62	33	930	1,120	—	1,850	64	49
Nummulite limestone (Rosenheim)	115	58	1,220	1,320	1,200	1,240	95	73
Diabase (Ochsenkopf) .	—	—	—	2,340	—	2,500	—	—
Syenite (Wölsau) . .	—	—	—	1,700		1,740	—	—

Other Researches.—The following tests were made by Dr. Böhme[1] of cubes about 10 × 10 × 10 inches of rubble limestone masonry, set in different mortars. The cubes were three months old:

Mortar	Mean crushing strength in tons per sq. ft.
1 cement, 3 sand	123·4
1 „ 6 „	69·6
1 cement, 7 lime, 16 sand . . .	64·3
1 lime, 2 sand	46·5

[1] *Mitt. a. d. K. Techn. Versuchsanstalten zu Berlin*, 1884, p. 86.

CRUSHING STRENGTH OF STONE

Description	Tons per sq. ft.	Authority
GRANITES:		
Mount Sorrel	832	Fairbairn
Aberdeen grey (2-inch cube)	1,412	Unwin
„ „ (cylinder, $2\frac{1}{8}$ inches diameter, $3\frac{1}{4}$ inches high)	1,162	„
Aberdeen red (2-inch cube)	1,614	„
„ „ (cylinder, $2\frac{1}{8}$ inches diameter, $3\frac{1}{4}$ inches high)	1,357	„
Gneiss (Kistna Bridge, India) ($2\frac{1}{4}$-inch cubes)	787–1,930	„
Quartz	1,270	Mallet
BASALTS:		
Penmaenmawr (2-inch cube)	1,086	Fairbairn
Hornblendic greenstone	1,580	Wilkinson
Felspathic „	1,106	„
SLATES:		
Compact Welsh clayslate (3-inch cubes)	733–1,052	Unwin
Slate	1,205	Mallet
Valencia (Irish) (1-inch cubes)	720	Wilkinson
Killaloe „ „	1,974	„
SANDSTONES:		
Bramleyfall	389	Rennie
Craigleith (2-inch cube)	504	Roy. Com.
Darley Dale „	455	„ „
Giffneuk „	310	„ „
Kenton „	318	„ „
Morley Moor „	318	„ „
Park Spring „	487	„ „
Stanley „	383	„ „
Runcorn (sixteen 4-inch cubes)	267–443	Unwin
„ (six 3-inch cubes)	295–416	„
„ (six 4-inch cubes)	427–514	„
York grit (3-inch cube)	712	„
Red Mansfield „	609	„
„ „ (2-inch cubes)	327	Roy. Com.
White „ „	337	„ „
Red Alton (3-inch cubes)	309	Unwin
Sydanape „	490	„
Scotgate Head	475	„
LIMESTONES:		
White Italian marble	1,400	Rennie
White statuary „	206–389	„
Portland	239–292	„
„ (4-inch cube)	516	Unwin
„ (2-inch cube)	250	Roy. Com.
Purbeck ($1\frac{1}{2}$ inch cube)	587	Rennie
Ancaster (2-inch cube)	150	Roy. Com.
Barnac „	114	„ „
Ketton „	164	„ „
„ (3-inch cube)	312	Unwin

CRUSHING STRENGTH OF STONE—*continued*

Description	Tons per sq. ft.	Authority
Ketton rag (2-inch cube) . .	577	Roy. Com.
Bath Box ground (3-inch cube)	107	Unwin
„ „ (2-inch cube)	95	Roy. Com.
Bolsover (2-inch cube) . .	484	„ „
Bramham Moor „ . .	380	„ „
Brodsworth „ . .	295	„ „
Cadeby „ . .	104	„ „
Chilmark „ . .	409	„ „
Hamhill „ . .	259	„ „
Huddlestone „ . .	278	„ „
Park Nook „ . .	278	„ „
Roche Abbey „ . .	250	„ „
Tottenhoe „ . .	124	„ „
Caen (3-inch cube) . . .	198	Unwin

BRICKS

278. Bricks are made from clays, loams, or marls containing silicate of alumina, mixed with sand, oxide of iron, and carbonates of lime and magnesia. The plastic, strong, or pure clays contract very much in burning, and do not vitrify, so that the bricks are not durable. Sand diminishes contraction, and permits partial vitrification in burning. Iron acts as a flux, facilitating fusion of the silica, and, in many cases, determines the colour of the bricks. Lime diminishes contraction, and acts as a flux; but lumps of lime become quicklime in burning, and, slaking afterwards, cause the brick to crack. The following short summary gives the composition of some clays:

Material	Burham clay	London brick clay	Loam	Marl
Silica and alumina . .	63·3	83·8	93·7	43·0
Oxide of iron . . .	5·0	7·7	1·3	3·0
Carbonate of lime . .	18·9	1·4	0·5	46·5
Carbonate of magnesia .	0·1	5·1	—	3·5

Malm is clay mixed with chalk in a wash mill.

Bricks are either hand-moulded or machine-moulded. In the latter case the clay may be wet and plastic, or dry or semi-dry. Hand-made bricks have usually a cavity, or frog, on one side, which is supposed to afford a key for the mortar. Wire-cut machine-made bricks have necessarily no cavity or frog. Some pressed bricks have frogs on both sides. Bricks are either 'clamp burned' or 'kiln burned.' The weight of bricks varies a good deal. London stocks weigh about

6·8 lbs. Pressed bricks and blue bricks may weigh 10 lbs. Ordinary red bricks weigh about 7 lbs., while some of the lightest weigh only 5½ to 6 lbs. The absorption of water by bricks also varies. Staffordshire blue bricks absorb 2 to 6 per cent. of their weight; ordinary stocks and red bricks, 7 to 10 per cent.; and the softer and more porous bricks, 20 per cent.

The following table gives the crushing strength of a variety of bricks. It may be added, however, that Mr. Ward gives some tests of bricks of exceptional strength.[1] In these tests Staffordshire blue bricks carried 650 to 1,064 tons per sq. ft., and bricks made of slate débris 1,056 tons per sq. ft.

CRUSHING STRENGTH OF BRICKS (UNWIN)

(Single bricks. Faces made smooth and parallel by plaster of Paris)

Description	Dimensions	Cracked at tons per sq. ft.	Crushed at tons per sq. ft.	Colour	Remarks
London stock max.	9·2 × 4·3 × 2·8	—	185	—	Twelve from different localities
,, ,, min.	8·8 × 4·0 × 2·5	84	89	Yellow	
,, ,, mean	9·0 × 4·2 × 2·6	—	121	—	
Aylesford, common .	8·9 × 4·4 × 2·7	48	183	Pink	
,, ,, .	8·9 × 4·4 × 2·7	111	228	,,	
,, pressed .	9·1 × 4·3 × 2·7	71	141	Red	Frog
Candy, pressed . .	8·8 × 4·3 × 2·8	80	381	—	
Rugby, common . .	9·5 × 4·2 × 2·9	158	190	Red	
,, ,, . .	9·0 × 4·2 × 3·0	—	120	,,	
Lodge Colliery, Notts .	9·0 × 4·2 × 3·4	127	159	,,	
,, ,, ,, .	9·0 × 4·2 × 3·3	55	122	,,	
Digby Colliery, Notts .	4·6 × 4·2 × 3·2	—	414	,,	Half-brick
Ruabon, pressed . .	8·8 × 4·3 × 2·7	361	not crushed	,,	
Grantham, wire-cut .	9·2 × 4·2 × 3·2	—	83	Red	
Leicester ,, .	8·9 × 4·5 × 3·2	228	246	,,	
,, ,, .	9·1 × 4·2 × 2·8	115	229	,,	
,, ,, .	4·4 × 4·2 × 2·7	225	365	,,	Mean of 7 half-bricks
Cranleigh, pressed .	4·7 × 4·6 × 2·5	149	181	,,	Half-brick, frog
,, ,, .	4·6 × 4·6 × 2·5	165	237	,,	
Gault, wire-cut max.	8·9 × 4·3 × 3·0	119	198	White	,, ,,
,, ,, min.	8·7 × 4·1 × 2·7	89	145	,,	
,, ,, mean	8·8 × 4·2 × 2·8	—	178	,,	
Arlesley white max.	9·1 × 4·2 × 2·9	—	207	,,	
,, ,, min.	8·8 × 4·1 × 2·7	50	107	,,	
,, ,, mean	8·9 × 4·2 × 2·7	—	161	,,	
,, ,, wire-cut	9·0 × 4·2 × 2·7	151	239	,,	
Coventry . . .	4·5 × 4·4 × 3·0	—	256	Red	Half-brick
Fletton . . .	8·6 × 4·2 × 2·7	137	203	Pink	

[1] *Proc. Inst. of Civil Engineers*, lxxxvi. p. 24.

CRUSHING STRENGTH OF BRICKS—*continued*

Description	Dimensions	Cracked at tons per sq. ft.	Crushed at tons per sq. ft.	Colour	Remarks
Fletton . . .	8·8×4·1×2·7	126	169	Pink	
„ . . .	8·6×4·2×2·7	199	239	„	
Glazed brick . .	8·8×4·4×3·3	69	166	White	Frog
„ „ . .	8·9×4·4×2·9	166	174	„	„
Kentish stock max.	9·3×4·4×2·9	107	127	Yellow	
„ „ min.	9·1×4·3×2·8	30	54	„	
„ „ mean	9·2×4·4×2·9	—	82	„	
Newcastle . . .	9·0×4·5×2·5	—	249	„	
„ . . .	9·1×4·4×2·6	155	237	Blue	
Staffordshire blue, max.	9·0×4·5×3·2	763	807	„	Nineteen half-bricks
„ „ min.	8·9×4·1×2·7	152	296	„	
„ „ mean	9·0×4·2×2·9	—	564	„	
Stourbridge . .	8·8×4·3×2·8	157	209	Yellow	
„ . . .	9·0×4·3×2·8	161	242	„	
„ . . .	9·0×4·3×2·7	—	300	„	
Red rubbers max.	10·1×4·9×3·4	—	93	Red	
„ . . min.	9·9×4·8×3·3	36	67	„	
„ . . mean	10·0×4·9×3·4	—	77	„	
„ three in column, bedded in putty	9·0×4·5×8·0	—	25	„	
Terracotta block . .	6 sq. ins.	—	168		
„ „ . .	15 „ „	—	139		
„ „ . .	15 „ „	—	267		
„ „ . .	6 „ „	—	104		

279. *Strength of Brickwork.*—Comparatively few accurate tests have been made of the strength of brickwork masses. The following results of tests of brick cubes, with different

Mortar	Condition	Mean crushing strength in tons per sq. ft.	Crushing strength of single brick, tons per sq. ft.	Crushing strength of mortar in cubes, tons per sq. ft.
Beneckendorfer brick:				
1. 1 lime, 2 sand . .	Dry	116·2	263·2	11·4
2. 7 lime, 1 cement, 16 sand	Dry	130·4	„	42·0
3. 1 cement, 6 sand . .	Dry	139·4	„	112·4
4. „ „ . .	Wet	141·9	„	„
5. 1 cement, 3 sand . .	Dry	158·8	„	192·9
6. „ „ . .	Wet	169·8	„	„
Hertzfelder brick:				
7. 1 lime, 2 sand . .	Dry	70·0	160·9	11·4
8. 7 lime, 1 cement, 16 sand	Dry	73·3	„	42·0
9. 1 cement, 6 sand . .	Dry	93·2	„	112·4
10. „ „ . .	Wet	87·4	„	„
11. 1 cement, 3 sand . .	Dry	100·7	„	192·9
12. „ „ . .	Wet	104·6	„	„

mortars, were made at Berlin by Dr. Böhme. The brick cubes were approximately 10 × 10 × 9·5 inches, and were three months old. Two kinds of brick were used.

This gives for the ratios of strength of brickwork to strength of single bricks:

For mortar of 1 lime, 2 sand	0·44
„ „ „ 7 lime, 1 cement, 16 sand	0·48
„ „ „ 1 cement, 6 sand	0·55
„ „ „ 1 cement, 3 sand	0·63

280. *Tests of Bricks and Brick Piers at Toronto.*—Messrs. Wright and Keele have carried out some interesting tests at the laboratory of the School of Practical Science, Toronto. The following table gives a summary of the results. The single bricks were tested, prepared with parallel faces of Portland cement. Five-inch cubes of the lime mortar used, at 2½ months' age, crushed with 65 lbs. per sq. in.; similar cubes of the cement mortar at the same age with 1,352 lbs. per sq. in. In the table the ratio of the strength of the piers to the strength of single bricks has been calculated:

Brick used	Section of pier, inches	Height of pier		Age of pier months	Crushing strength, tons per sq. ft.		
		Courses	Inches		Single brick	Pier	Ratio
Piers in lime mortar, 2 sand to 1 lime							
Kingston Road, 1st	8·8×8·8	8	23	2½	242	40·2	·166
„ „ 2nd	9 ×9	8	24	„	108	?	—
„ „ 3rd	9 ×9	8	24	„	118	21·3	·181
Humber, 1st	9 ×9	8	24	„	85	24·8	·292
„ 2nd	8·7×8·7	8	23½	„	119	21·0	·177
Carleton clinker, 1st	8·6×8·6	8	22	„	364	43·8	·121
„ „	8·7×8·7	8	23½	„	205	38·5	·188
Yorkville, 1st	8·7×8·7	5	14½	„	297	36·6	·123
„ 2nd	8·7×8·7	8	23½	„	200	28·2	·141
Don Valley Buff	8·6×8·6	8	21	„	229	49·4	·216
„ „ Red	8·5×8·5	8	21½	„	344	87·7	·255
Piers in cement mortar, 3 sand to 1 Portland cement							
Yorkville, 1st	8·6×8·6	8	24	2½	297	76·5	·258
„ 2nd	8·7×8·7	8	24	„	200	73·3	·366
Humber, 2nd	9 ×9	8	24	„	119	81·4	·684
Kingston Road, 2nd	9 ×9	8	23½	„	108	61·3	·568
Carleton clinker	8·5×8·5	8	22¾	„	364	173·4	·476

281. *Watertown Tests of the Strength of Brickwork.*—Tests of brickwork piers were made by a committee of the American Society of Civil Engineers in 1887–8. The bricks used were of three kinds:

	Crushing strength in tons per sq. foot.
Hard burned face bricks	890
„ „ common bricks	1,170
Bay State medium bricks	730

Thirty-three brick piers were built of these bricks of various forms and sizes. The bricks were laid on the bed with joints broken in every course, except in two instances. The age of the piers when tested varied from fourteen to twenty-four months. The tests were made with the 500-ton Emery Machine at Watertown. The mortar used was made with Portland cement, with Rosendale (American) cement, with lime, and with a mixture of lime and cement. In the table the proportions are given; P, R, L, and S meaning Portland, Rosendale, lime, and sand. The following tables give the results.

282. *Tests of Brick Piers by a Committee of the Institute of British Architects.*[1]—Under the direction of a committee a series of piers of large size were built of five varieties of brick and with both lime and cement mortar. These piers were 6 feet in height and generally 18 inches square. The piers of Staffordshire blue bricks were 13½ inches square. They were crushed in a very large hydraulic press having a ram 3 ft. 1⅞ in. in diameter. The upper part of the ram had a cup and ball bearing. The pressure in the ram cylinder was determined by tested pressure gauges. In order to determine exactly the relation between the pressure on the ram and the effective thrust exerted by it the following method was adopted. A series of copper cylinders were prepared about 0·9 and 1·1 inches diameter and 1·9 and 2·1 inches in height. Some of these were compressed in a testing-machine, and the relation of the loads and compressions determined. Others were crushed in the hydraulic press, and the relation between the pressure-gauge pressures and the compressions was observed. Then it was possible, by comparing the two series of results, to find the effective

[1] *Journal of the Royal Institute of British Architects*, Third Series, vol. iii. p. 333; vol. iv. pp. 73 and 121; vol. v. pp. 77 and 129.

BRICK PIERS IN CEMENT MORTAR (WATERTOWN)

Kind of brick	Mortar	Form of pier	Nominal size, inches square	Area of section in sq. ft.	Height in inches	No. of courses	Thickness of joints, ins.	Age in months	Crushing strength in tons per sq. ft.	Ratio of strength of pier to strength of brick	Means
Common	1 P. and 2 S.	Solid	16	1·56	121	49	$\frac{1}{4}$	24	121	·104	·107
,,	,,	,,	12	0·95	120	58	$\frac{1}{4}$	24	128	·110	
Face	,,	,,	12	0·91	119	51	$\frac{3}{16}$	$23\frac{1}{2}$	144	·162	·162
,,	,,	,,	8	0·40	80	35	$\frac{1}{8}$	23	144	·162	
,,	,,	,,	12	0·92	$23\frac{1}{2}$	10	$\frac{1}{6}$	$18\frac{1}{2}$	234	·263	·263
Common	,,	,,	16	1·77	$23\frac{1}{2}$	13	$\frac{1}{8}$	$18\frac{1}{2}$	not given	—	—
Bay State	1 R., 2 L., and 6 S.	,,	12	1·00	$73\frac{5}{8}$	30	$\frac{3}{16}$	$20\frac{1}{2}$	105	·144	·144
,,	1 R. and 2 S.	,,	12	1·00	$72\frac{1}{8}$	30	$\frac{3}{16}$	20	126	·173	·173
,,	1 P. and 2 S.	,,	12	1·00	$72\frac{5}{8}$	29	$\frac{3}{16}$	20	115	·158	·158
,,	1 P., 2 L., and 6 S.	,,	12	1·00	$73\frac{3}{8}$	30	$\frac{3}{16}$	$20\frac{1}{2}$	91	·125	·125
,,	Neat P.	,,	12	1·00	72	30	$\frac{3}{16}$	$19\frac{1}{2}$	152	·209	·209

The pier built with neat Portland cement, and the very short pier, are stronger than the others. For the others, the crushing strength of the pier is from 11 to 17 per cent. of the strength of the bricks.

BRICK PIERS IN LIME MORTAR (WATERTOWN)

Kind of brick	Mortar	Form of pier	Nominal size inches square	Area of section in sq. ft.	Height in inches	No. of courses	Thickness of joints, ins.	Age in months	Crushing strength in tons per sq. ft.	Ratio of strength of pier to strength of brick
Face	1 L., 3 S.	Solid	8	0·395	17	7	—	15	163	·184
Common	,,	,,	8	0·420	17	7	—	15	156	·134
Face	,,	,,	12	0·92	24	10	—	$18\frac{1}{2}$	125	·141
,,	,,	Hollow	12	0·79	24	10	—	$18\frac{1}{2}$	128	·144
Common	,,	Solid	12	0·96	24	10	—	$18\frac{1}{2}$	138	·118
,,	,,	Hollow	12	0·83	24	10	—	$18\frac{1}{2}$	131	·112
Bay State	,,	Solid	12	1·01	24	10	—	$18\frac{1}{2}$	88	·121
,,	,,	,,	12	1·00	$72\frac{1}{2}$	30	$\frac{3}{16}$	$19\frac{1}{2}$	73	·100
,,	,,	,,	12	1·00	$72\frac{1}{4}$	30	$\frac{3}{16}$	20	85	·117
,,	,,	,,	12	1·08	73	19[1]	$\frac{1}{8}$	20	78	·107
Face	,,	,,	8	0·40	80	35	$\frac{1}{8}$	23	120	·135
Bay State	,,	,,	12	1·00	$94\frac{1}{4}$	39	$\frac{3}{16}$	$23\frac{1}{2}$	75	·104
,,	,,	,,	12	1·00	$119\frac{5}{8}$	49	$\frac{3}{16}$	$23\frac{1}{2}$	59	·081
Common	,,	Hollow	12	0·80	$120\frac{3}{8}$	50	$\frac{1}{4}$	24	101	·087
,,	,,	Solid	12	0·96	$117\frac{3}{8}$	49	$\frac{1}{4}$	24	76	·065
Face	,,	,,	12	0·92	$119\frac{7}{8}$	52	$\frac{3}{16}$	24	97	·109
,,	,,	Hollow	12	0·80	$119\frac{1}{8}$	52	$\frac{1}{8}$	24	115	·130
Bay State	,,	Solid	12 × 16	1·33	$120\frac{1}{2}$	49	$\frac{1}{4}$	24	50	·069
,,	,,	,,	8 × 12	0·66	$120\frac{3}{4}$	49	$\frac{1}{4}$	24	60	·082

[1] On edge.

In the hollow piers the space was about $4\frac{1}{2}$ inches square. The strength decreases in a marked way with increase of height. For piers not over 24 inches in height, the strength is 12 to 18 per cent. of the strength of the bricks. For piers about 120 inches in height, the strength is 7 to 13 per cent. of the strength of the brick. In these tests the strength of piers built with cement is about 60 per cent. greater than that of piers built with lime mortar.

thrust of the ram corresponding to any pressure shown on the gauge. In the first series of tests, for instance, it was found that the ram friction varied from 5 tons with 10 lbs. per sq. in. in the ram cylinder to 10 tons with 130 lbs. in the ram cylinder. If p is the pressure on the gauge in lbs. per sq. in., then the effective thrust of the ram in tons was found to be

$$T = 0{\cdot}464\,p - 4{\cdot}5.$$

The operation of finding the ram friction was repeated for each series of tests, and the friction was a little different for each series.

The cement mortar was mixed by measure, the proportions being 1 cement to 4 washed river sand. The grey lime mortar was mixed in the proportion of 1 to 2.

Unfortunately the piers first built were not very well built, or the mortar was not quite satisfactory. The piers of the second and third series were built under more careful inspection, and were stronger. The following table gives the results. The ratio of strength of pier to strength of brick has been calculated for the third series.

CRUSHING STRENGTH IN TONS PER SQUARE FOOT

Mortar	Age, months	Stocks	Gault	Fletton	Leicester red	Stafford blue
Single brick	—	84	189	221	362	780
Sand pier	—	—	—	—	15	—
First Series						
Lime	3½	10·4	21·9	—	30·7	74·3
„	10	12·5	21·6	—	34·1	73·7
Cement	3½	14·9	17·8	—	58·5	72·8
„	10	19·7	30·0	—	50·4	82·5
Second Series						
Lime	3½	18·3	—	—	—	—
Cement	3½	—	49·6	—	86·4	103·1
Third Series						
Lime	5	18·6	31·1	30·7	45·4	114·3
Cement	5	39·3	51·3	56·3	83·0	135·4

Ratios of Strength of Piers to that of Single Bricks.
Third Series

Lime . . .	5	·22	·16	·14	·13	·15
Cement . . .	5	·47	·27	·25	·23	·17

It will be seen that in the case of the brick cubes tested by Dr. Böhme, the strength was about 0·46 for lime mortar and 0·59 for cement of the strength of single bricks. The piers 24 ins. high tested at Toronto had from 0·121 to 0·292 of the strength of single bricks when built with lime, and 0·258 to 0·684 when built with cement. In the Watertown tests on piers 24 to 120 ins. high the ratio varied between 0·07 and 0·18 for lime mortar, and between 0·11 and 0·26 for cement. In the Institute of British Architects' tests with piers 18 ins. square and 72 ins. high, the ratio varied between 0·13 and 0·22 for lime mortar, and 0·17 and 0·47 for cement. There is a tolerably clear relation between the height of the pier and its strength, the strength being least for the piers in which the ratio of height to diameter is greatest.

There is one pier in the Institute's series which is rather interesting. This is the pier of Leicester red bricks, built dry, with merely a layer of sand in the joints. It carried 15 tons per sq. ft., or about half as much as similar piers built with lime mortar tested after 3 and 10 months.

283. *Manchester Experiments.*—Mr. W. C. Popplewell has carried out a very accurate series of tests of brickwork piers at the Municipal School of Technology.[1] The brickwork piers were approximately 18 ins. × 18 ins. × 3 ft. high. In most cases the apparent limit of proportionality and elastic modulus were determined as well as the crushing load. The bricks were set in lime mortar (2 sand, 1 lime); in Portland cement mortar (3 sand, 1 cement); in black lime mortar, and in lias lime mortar. In the following table the coefficient of elasticity is given for the first and subsequent loadings.

The wire-cut bricks tested singly crushed with 264 tons per sq. ft.; the Accrington with 250; the Staffordshire with 356; and the blue brindle with 485.

[1] *Proc. Inst. Civil Eng.*, clxi.

Brickwork Piers (Popplewell)

No.	Brick	Mortar	Age, weeks	Limit of proportionality. Tons per sq. ft.	Cracking stress. Tons per sq. ft.	Crushing stress. Tons per sq. ft.	Coefficient of elasticity. Tons per sq. ft.	Ratio of strength of pier to that of brick
1	Wire cut .	Lime . .	4	—	35	53	—	·20
2	„ „ .	Cement .	39	25	64	84	82,000	·32
	„ „ .	„	„	„	„	„	90,000	—
3	Accrington	Black lime	4	24	78	96	51,400	·38
4	Blue Staf-ford .	Cement .	39	55	69	98	91,300	·28
	„	„	„	„	„	„	94,500	—
	„	„	„	„	„	„	121,000	—
5	Brindle .	Black lime	12	22	100	165	87,400	·34
	„	„	„	„	„	„	86,800	—
	„	„	„	„	„	„	86,800	—
	„	„	„	„	„	„	97,000	—
6	Brindle .	Black lime	25	40	110	185	167,500	·38
	„	„	„	„	„	„	161,200	—
	„	„	„	„	„	„	162,000	—
	„	„	„	„	„	„	149,800	—
7	Brindle .	Cement .	12	35	132	169	125,000	·35
	„	„	„	„	„	„	124,000	—
	„	„	„	„	„	„	121,000	—
8	Brindle .	Cement .	26	30	90	161	127,000	·33
	„	„	„	„	„	„	132,000	—
	„	„	„	„	„	„	122,000	—
9	Brindle .	Lias lime .	12	10	38	119	34,900	·25
	„	„	„	„	„	„	40,100	—
	„	„	„	„	„	„	44,200	—
10	Brindle .	Lias lime .	26	10	41	102	25,500	·21
	„	„	„	„	„	„	38,500	—
	„	„	„	„	„	„	41,000	—

CHAPTER XIX

LIMES AND CEMENTS

284. Limes and cements are of the greatest importance to the engineer, and, being artificially-manufactured products, they vary in quality according to the care exercised in the selection of the materials of which they are made, and the skill and attention with which the processes of manufacture are carried on. To secure a uniform and trustworthy cement, the engineer has been driven to test regularly the cement supplied. To Mr. Grant is largely due the credit of establishing systematic tests of cement, with the result that, from the pressure brought to bear on manufacturers, and the knowledge gained of the conditions on which the strength of a cement depends, there has been achieved a very considerable and general improvement of quality. The cost of testing forms but a small percentage on the value of the cement, and as the quality of cement may vary through very wide limits, from qualities absolutely trustworthy to qualities absolutely dangerous, the cost of testing is fully repaid by the greater value of the cement obtained, and the thorough confidence with which after testing it can be used.

The cementing materials ordinarily used are classified thus:

1. Rich or fat limes.
2. Poor limes.
3. Hydraulic limes.
4. Hydraulic cements.

The rich or fat limes are produced by the calcination of nearly pure limestones, and they consist of quicklime (CaO) nearly free from other ingredients. Such limes, when mixed with water, slake violently, and afterwards set or harden extremely slowly, if at all, by the absorption of carbonic acid from the air. Fat limes make very weak mortar. Poor limes contain 10 to 40 per cent. of sand, alumina, &c. They

slake much less violently, or even imperfectly, and also make a very weak and very slowly setting mortar.

Hydraulic limes and cements are those which contain ingredients capable of combining and hardening, apart from any absorption of carbonic acid from the air. They will, therefore, set under water. The hydraulic limes contain lime, so that they slake. But they contain also alumina, silica, or other ingredients in a condition capable of producing chemical action in the presence of water. This action results in the setting of the lime, which hardens and becomes insoluble. Feebly hydraulic lime makes mortar which hardens enough to resist a finger-nail in a month. The Lias and Mountain limestones yield limes more actively hydraulic.

Artificial hydraulic cements are mixtures of lime and clay in proportions which produce eminent hydraulic or setting properties. The mixture is calcined to clinker at a suitable temperature, and then ground to a fine powder. Such a cement hardly slakes at all, but sets with rapidity, becoming in course of time extremely hard.

285. *Portland Cement.*—About the year 1850 there was first produced a new cement, which from its resemblance to Portland stone when set was called Portland cement. It has the properties of setting rapidly and setting under water, and it slowly hardens to a condition in which it is nearly as strong as natural stone. It has the very important quality of altering extremely little in volume in hardening. It rapidly established its superiority as a constructive material to Roman cement, and in spite of its greater cost it has for most purposes supplanted hydraulic lime. It can be kept with little deterioration and shipped to distant countries. Its use has extended till its manufacture has become one of the most important industries in this country, in Germany, in France, and in the United States.

Experience shows the proportion of the natural materials used which is most suitable. These materials must be so mixed that the cement is homogeneous and invariable in composition. At first, the chalk and clay were ground together with a large volume of water into a liquid slip. Now it is found that grinding with only 35 per cent. of water is not only economical, but prevents the segregation of materials which took place in fluid slip. With some materials no water is used in grinding. The mixed materials are then calcined

to a clinker at a temperature just short of that which produces fusion or vitrification. Underburnt clinker is weak, and overburnt clinker is an almost inert cement. Lastly, the clinker must be broken up and ground to a powder, so fine that the cement particles expose a maximum surface at which chemical actions may occur, and are not too large to fill the smallest interspaces in the sand with which the cement is mixed in use.

The hydraulicity of a cement is due to the silica, alumina, and oxide of iron. There should be no excess of lime, that is more than enough to saturate the silica and alumina. Let x, y, and z be the percentages of lime, silica and alumina in a cement, and 56, 60, and 102 their molecular weights. Then—

$$\frac{x}{56} \Big/ \left(\frac{y}{60} + \frac{z}{102}\right)$$

should not exceed 2·85 or be less than 2·0. The calcination removes carbonic acid and water, and leads to the formation of calcium silicate, calcium aluminate, and calcium ferrate. In the setting and hardening of a paste formed of the cement, there is probably a hydration of the silicates, and the formation of double hydrated silicates.

The composition of a Portland cement varies more or less, but generally lies between the limits given in the following table:

	Per cent.
Silica	20–28
Alumina	5–10
Oxide of iron	2–6
Lime	65–58
Magnesia	0·5–3·0

286. *Soundness of Portland Cement.*—The most dangerous quality of a cement is a tendency to expand, crack or blow, or even to disintegrate after it has set hard. Excess of lime or underburning causes a cement to be unsound, both leading to the presence in the cement of 'free' or loosely-combined lime. Some cements which are unsound when quite fresh are rendered sound by 'seasoning' or exposure to air in thin layers. Magnesia and gypsum have a tendency to render a cement 'blowy.'

A common test for soundness is to gauge a pat 4 to 6 inches diameter and about $\frac{1}{8}$-inch thick, thin at the edges,

on a glass plate. After setting for twenty-four hours in moist air the pat is placed in water at 58°–64° F. The pat should show no tendency to crack, blister, or curl in seven days. With a few cements the cracking is not shown till after a longer time. Mr. Faija suggested hastening the test by exposing the pat to a temperature of 110°–115° F. for twenty-four hours. Both these tests are now generally abandoned.

Lechatellier Test.—This is the test for soundness which has now superseded the rougher tests formerly used. It is essentially a test of the tendency to expand. The apparatus consists of a small split cylinder of brass (fig. 197).

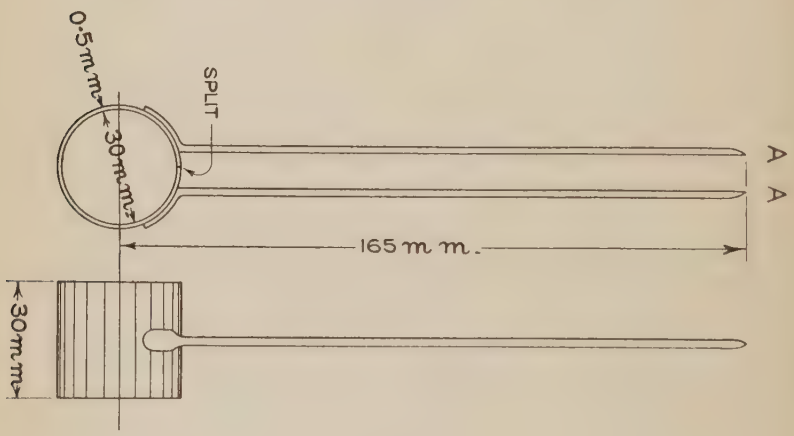


Fig. 197.

On each side of the split there is an indicating finger A. This is placed on a plate of glass and filled with cement gauged in the usual way. It is then covered with another plate of glass loaded with a small weight. It is immediately placed in water at 58° to 64° F., and left for twenty-four hours. The distance between the points of the fingers is then measured. The apparatus is next placed in cold water, which is raised to boiling point gradually and kept boiling for six hours. The apparatus is then removed, allowed to cool, and the distance of the points is again measured. The difference of the measurements is proportional to the expansion. Usually the cement is aërated for twenty-four hours in a layer 3 inches thick before gauging. The movement of the

fingers should not exceed 10 mm. after twenty-four hours' aeration or 5 mm. after seven days' aeration.

Some tests by Mr. A. C. Davis [1] show the dependence of the expansion on the amount of aeration before gauging.

LECHATELLIER TEST (DAVIS)

Twenty-four hours in cold, six in boiling water. Expansion in mm.

Cement	Fresh	Aeration				
		3 days	7 days	14 days	21 days	28 days
I. In bulk . . .	36	33·5	31	20	12	5
In layer 1″ thick .	32	30	27	15	7·5	4
II. In bulk . . .	1·75	1·5	1·0	0·75	0·5	nil
In layer 1″ thick .	—	1·0	nil	nil	nil	nil

287. *Measurement of Expansion of Cement.*—Bauschinger used cubes of cement 4·8 inches length of side. Twenty-four hours after mixing, a small brass plate, about $\frac{4}{10}$ inch diameter, was fixed into two opposite sides of the cube, by cementing. After forty-eight hours' hardening, the accurate measurements between the brass plates were commenced. The cube was placed in a measuring instrument, having a spring touch-lever on one side and a micrometer screw on the other. The touch-lever insured the constancy of pressure between the measuring points and the block to be measured. The pitch of the screw was very accurately determined; and as a perfectly constant temperature cannot be ensured in experiments lasting a long time, a correction for the expansion of the cement blocks by heat was determined.

Neat cement briquettes hardened in air sometimes showed a small expansion at first, but all ultimately shrank in volume. Neat cement briquettes hardened in water all showed a very small expansion, generally less than ·05 mm. in 120 mm. length in sixteen weeks. With briquettes mixed with sand the changes of volume were of the same kind, but smaller.

288. *The Deval Test.*—From the results of a careful investigation (*Journal of Soc. Chem. Industry*, 1891) Deval established the fact that, in most cases, a sand briquette (1 to 3)

[1] *Proc. Inst. Civil Eng.*, clxxv. 280.

kept in water at a temperature of 176° F. for two days has the same strength as one kept in water at ordinary temperature for seven days. Also that such a briquette kept in water at 176° F. for seven days had the same strength as one kept at ordinary temperature for 28 days. If the briquettes are made from an unsound cement, they have little strength, or even disintegrate, when treated by the Deval process. Messrs. Stanger and Blount have found this rule to be practically true, but they find that few English cements will stand the test unless previously aerated.

289. *Heaviness of Cement.*—It was early discovered that heavy, well-burnt clinker produced better cement than the lighter underburnt clinker. Hence for a long time it was prescribed in all specifications that the cement should have a certain weight per bushel (= 1·283 c. ft.). A good Portland cement, ground so that the residue on a 76 sieve is 10 per cent., weighs 108 to 110 lbs. per bushel.

To get uniform results the cement is sifted through a very coarse sieve, and allowed to fall through a funnel 18 inches to 3 feet high into the standard measure. The cement is strickled off, and the measure weighed without shaking. The size of the measure must be defined, as the cement packs closer in a large than in a small measure. Bauschinger found 13 per cent. difference between the weight of cement in a 50-litre and a 1-litre vessel. But another influence affects the result. A cement ground coarsely will give a heavier weight than the same cement ground finely, so that the weight test is a premium on coarse grinding. Since this has been understood, the weight test has been generally abandoned.

Real Density or Specific Gravity of Cement.—The weight per bushel is the apparent density of cement, and the real density can only be inferred from it for cements of equal fineness. The question whether a cement is well burnt is more safely answered by a determination of the real specific gravity, and that test has now come into use. The specific gravity may be determined by any of the methods in use for granular bodies, but the cement cannot be immersed in water, which causes hydration and alteration of volume. Benzine, petroleum spirit, or, perhaps better, turpentine dried by standing over quicklime may be adopted. An ordinary specific gravity bottle may be used, but then the specific gravity of the liquid must be accurately known. Hence

some form of volumenometer is generally employed. Mr. Blount has suggested the simple apparatus shown in fig. 198, a flask having a slender graduated neck. The lowest graduation mark is 14 c.c., and at that mark the flask has a capacity of 64 c.c. In use, 50 c.c. of oil of turpentine are first measured into the flask from a graduated pipette, the neck being kept dry. Then 50 grams of cement are introduced through a funnel. The air bubbles are more easily disengaged from the cement if it is added to the liquid instead of adding the liquid to the cement. For all ordinary cements the displacement for 50 grams lies between 14 and 20 c.c., so that this range of graduation is sufficient. The temperature at which a reading is taken must be that at which the turpentine was originally measured, and to get this temperature the flask may be put in a beaker of water. The specific gravity of a true fresh Portland cement should not be less than 3·15. Or if the test is made not less than four weeks after grinding 3·10

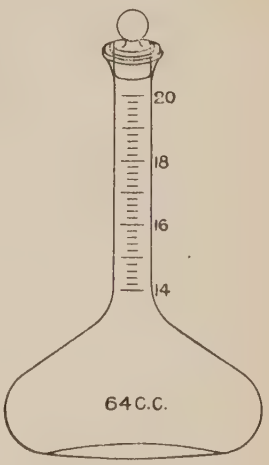


Fig. 198.

Fig. 199 shows an apparatus designed by M. Le Chatelier. It consists of a flask of a capacity of about 120 c.c. which has a neck about 20 cm. in length, with a bulb half-way up having a capacity of 20 c.c. Above the bulb the tube is graduated for a length corresponding to a capacity of 3 c.c., the divisions corresponding to 0·1 c.c. The diameter of the tube is 9 mm. In use, the flask is filled with benzine to the mark below the bulb, and 64 grams of the cement are gradually introduced through the funnel. By using a funnel reaching nearly to the upper part of the bulb risk of the cement blocking the tube is avoided. As the level of the benzine rises to the lowest point of the graduation the cement is introduced cautiously till the first graduation is reached. The volume of cement in the flask is then 20 c.c. Its weight is ascertained by deducting that of the portion left from 64 grams. Or the whole may be introduced and its volume ascertained by reading the benzine level on the graduation. The flask is kept in a vessel of water to avoid change of temperature.

290. *Fineness of Grinding.*—The greater part of the improvement in the quality of cement which has been effected in the last ten years has been due to the discovery of the importance of grinding the clinker to extreme fineness. The amount of surface the particles of cement expose increases inversely as the diameter of the particles. A cubic inch of cement would have 150 sq. ins. of surface if the particles were spherical and $\frac{1}{25}$ inch diameter, and 600 sq. ins. if they were $\frac{1}{100}$ inch in diameter; so that the area on which chemical action occurs increases as the cement is ground more finely. But probably this is only part of the explanation of the greater value of very finely ground cement.

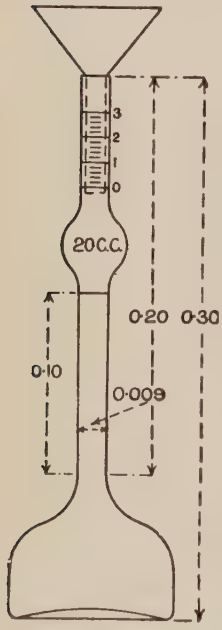


Fig. 199.

If cement is taken and sifted through a sieve of 50 meshes to the inch, the residue on the sieve of particles larger than the holes in the sieve will not adhere together sufficiently to form a briquette, except after a considerable time. They are almost without cementitious value. But if these same particles are reground, they are converted into valuable cement.[1]

The extremely small value of these larger particles in the cement was not for some time perceived. For a long time all tests of the strength of cement, or nearly all, were made with neat cement, the reason being that tests of this kind can be made more rapidly than any others. Now, a good cement will bear the addition of a certain amount of inert matter without any serious reduction of strength. Hence it happens that, in neat cement tests, a somewhat coarsely-ground cement gives results sometimes as high as a finely-ground one. But cement is never, in fact, used neat; it is used mixed with three to seven or more times its weight of the cheaper material, sand or gravel. In the German laboratories, therefore, it was thought desirable not to test the cement neat, but to test it in the condition in which it is used in practice, mixed with sand;

[1] On this point see a later investigation by Mr. Butler. *Proc. Inst. of Civil Engineers*, vol. cxxxii. p. 348.

and directly this was done, it was found that the cements which were strongest tested neat were by no means always strongest tested as mortar mixed with sand. The principal reason for this is that the finely-ground cement will bear a considerable addition of sand with less loss of strength than the coarsely-ground cement.

In the British Standard Specification it is provided that the residue on a sieve, when four ounces of cement are sifted for fifteen minutes, shall not exceed the quantity in the following table. The wire to be 0·0044 inch in diameter for the coarser and 0·002 inch for the finer sieve.

Sieve	Meshes per sq. in.	Residue
76×76 meshes	5,776	3 per cent
180×180 „	32,400	18 „ „

291. *Setting time.*—A very important point is the length of time required for a cement to definitely 'set.' The British Standard Specification recognises three grades. Quick cement, setting in ten minutes to thirty minutes; medium, in half an hour to two hours; and slow, in two hours to seven hours. Hydraulic limes are much slower. To determine the setting time, a 'Vicat needle' is used; that is, a vertical loaded rod, which can be gently lowered on the surface of a cement pat. The needle has a flat end 1 mm. square and weighs 300 grams. The cement is taken to be set when the needle just fails to make an impression. The cement is gauged as in making neat cement briquettes. The following table gives some results obtained by Mr. D. B. Butler as to the influence of temperature on the setting time: [1]

Sample	Temperature, Fahrenheit							
	100°	80°	60°	40°	100°	80°	60°	40°
	Initial set in minutes				Set hard in hours			
2	3	5	6	8	1	1¼	1¾	2½
3	4	10	15	20	½	¾	1½	6½
5	6	10	14	25	1	1½	2	2½
8	10	15	35	40	¾	1	1¼	1¾
11	19	32	60	120	3	6	7	15
12	15	35	70	360	3½	6	7	22

[1] Portland Cement. D. B. Butler, *Proc. Soc. of Engineers*, 1895.

292. *Tensile Strength of Cement.*—Although cement in use is generally in compression, a tensile test has been adopted as a criterion of quality, chiefly because it can be rapidly and easily made. Small briquettes of neat cement or cement and sand are used of a cross-section of one sq. in. or five sq. cm. The cement is gauged, placed in gun-metal moulds, left to harden for twenty-four hours in a moist atmosphere, and then placed in water. The tests of strength are made after seven and twenty-eight days. Usually six or ten briquettes are made and the mean result taken as the strength of the cement.

The form of the briquettes has a considerable influence on the strength. Fig. 200 shows some of the forms which have

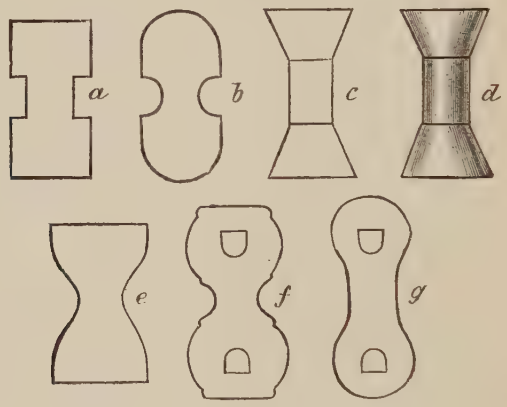


Fig. 200.

been used. Form *a*, used in the earlier tests, is a very bad form, the square corners producing unequal distribution of stress with a rigid material. In forms *f* and *g* a metal plate is inserted in the holes and takes the pressure of a knife-edge attached to each shackle. The form *e* is now almost universally used.

In some of Mr. Grant's tests, briquettes of the same cement gave strengths ranging from 280 lbs. per sq. in. for form *a*, to 460 lbs. per sq. in. for form *e*, at seven days after gauging. For some time briquettes with a section of $2\frac{1}{4}$ sq. ins. were used, but it is usual now to make the section 1 sq. in. The smaller briquettes are more easily moulded, and give more uniform results.

The briquettes are broken in small lever testing-machines,

of which there are now many in the market. It is very important that the load should be applied at a regular rate and

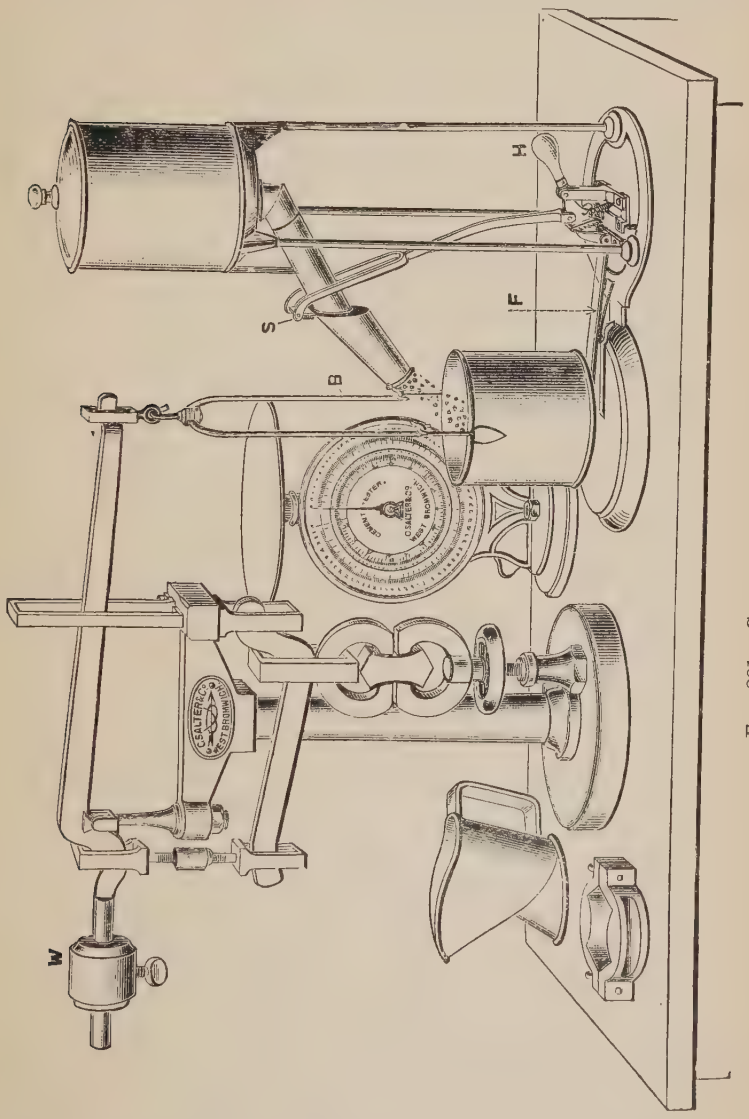


Fig. 201.—Cement-testing Machine.

without shock. Adie's machine is a single-lever machine with a rolling weight. Reid & Bailey's machine is a single-lever

machine, with a cistern at the end which fills with water to apply the stress. In Michele's machine, a bent or pendulum lever is used. Mr. Faija has designed a neat single-lever machine with a spring balance at the end. A worm and sector, acting on the spring balance, regularly increase the load. The ordinary German machine is a double-lever machine, and is loaded with shot.

A cement-testing machine of this type, made by Messrs. G. Salter & Co. of West Bromwich, is shown in fig. 201. A cast-iron column carries a pair of compound levers having a combined leverage of 50 to 1. The levers have steel knife-edges on concave steel bearings. A sliding balance weight is fitted to the upper lever. The upper briquette clamp hangs from the lower lever. The lower clamp is attached to the base of the column, and is adjustable by a screw. The upper lever is loaded by shot, and the supply of shot is automatically cut off when the briquette breaks.

To use the machine, set the levers floating by adjusting the balance weight w. Place the briquette in the clips. Hang the shot bucket on the bridle B, and screw down the small hand-wheel till the upper lever is as high as it can conveniently be. Press the handle H till the shot run at the desired rate. When the briquette breaks, the trip lever F closes the shutter S. The bucket and shot are then weighed on a spring balance. Maximum load on briquette 1,000 lbs.

293. *Precautions in Gauging Briquettes.*—A sample of the cement should be taken from every parcel of cement. Usually twelve samples are taken from different parts from the heap and mixed. The sample is spread out in a layer 3 inches deep for 24 hours before gauging. To obtain the highest results, the gauging must be done by a skilled workman with the smallest amount of water which will make a smooth stiff paste. Preliminary tests must be made, to ascertain exactly the quantity of water necessary. A small quantity of the mortar, dropped from the trowel at a height of 20 inches, should leave the trowel clean, and retain form without cracking. It should be capable of being moulded into a ball by hand which can be dropped 20 inches without cracking. Having ascertained how much water is necessary (18 to 25 per cent. of the weight of the cement usually in the case of neat cement), the cement and water for gauging should be accurately weighed.

The cement is usually gauged on a slate or iron slab, and

filled into the moulds. In Germany mechanical ramming is generally used, the cement being compressed into the mould by 100 strokes of a Boehme hammer. Briquettes of more uniform and somewhat greater strength are obtained in this way. In this country it is generally specified that the cement shall be placed in the moulds without mechanical ramming, the cement being filled into the moulds with a trowel and packed by the fingers or a light tool. The briquettes are removed from the moulds when set, allowed to remain 24 hours in a moist atmosphere, and then placed in fresh water renewed every 7 days. In testing the load should be uniformly increased at the rate of 100 lbs. in 12 seconds. In the British Standard Specification neat cement briquettes should carry 400 lbs. at 7 days from gauging and 500 lbs. at 28 days, and there are provisions as to the rate of increase of strength varying with the strength at 7 days.

294. *Briquettes of Sand and Cement.*—Briquettes of cement, mortar, or sand and cement give more trustworthy indications of the value of a cement than neat cement tests. The cement is always used in construction mixed with other materials, and the cement which is strongest neat is not always strongest tested with sand. The gauging of the briquettes also is easier, and the results are less affected by small variations of procedure.

The greatest difficulty of the sand test is securing an identical quality of sand for all tests which are to be compared. A sharp pit sand is best, which should be carefully washed and sifted. The sand used should be the portion which passes through a 20-mesh and remains on a 30-mesh sieve, the wires being ·0164 and ·0108 inch diameter respectively. In Germany, a special sand has been selected, and washed and sifted portions of this normal or standard sand are sold by the Government laboratories. In France, a standard sand is obtained by crushing quartzite, and sifting through sieves of practically the same-sized mesh as is given above. In this country, a sharp siliceous sand from a quarry at Leighton Buzzard is used as normal testing sand. M. Gary has experimented on eight samples of testing sand at the Versuchsanstalt in Berlin. Briquettes were prepared with Portland cement and sand in two proportions, 3 : 1 and 5 : 1. They were tested at 7, 28, and 90 days. Sharp-edged sands from America, Switzerland, and Cherbourg gave the greatest tensile strength, and the lowest resistance to compression.

Taking the strength of the briquettes of German normal sand, 3 : 1, as 100, the results with others were as follows :—

	Tension.	Compression.
Rhine Sand . . .	104	114
Austrian . . .	108	104
English	98	109
Swiss	111	81
Cherbourg . . .	110	81
American . . .	115	66

In the ordinary sand test, the mortar is gauged with one part by weight of cement and three of dried sand. The water required is about 12 per cent. of the weight of cement and sand. The sand and cement are mixed dry, the water added, and the mortar is gauged for five minutes. The briquettes are placed in water twenty-four hours after gauging.

The sand and cement briquettes should carry 150 lbs. per sq. in. 7 days from gauging and 250 lbs. at 28 days.

295. *Increase of Strength in Hardening. Initial Strength, and Rate of Gain of Strength.*—The constructional value of a building cement depends on two quite distinct elements—on its power of setting into a rigid form soon after it is gauged, and on its power of attaining in course of time a considerable strength. In the actual process of building, especially building under water, it is important that the cement should set rapidly, and gain strength enough to keep its form. But, generally, it is only after the lapse of months that the structure is called on to exert its full strength. Hence any strength acquired by hardening during that time is advantageous. Consequently, in judging of a cement from tests of its strength, both the initial strength acquired in a short time and the rate of gain of strength with age require to be considered.

Suppose experiments have been made, say, at seven days, four weeks, and twelve weeks. One would still like to be able to predict the strength at a greater age, and even in judging of the data in hand some difficulty arises from the discrepancies and anomalies incident to such experiments, and due to the difficulty of making the experiments numerous enough to get true average values. If anything were known of the law of increase of strength with age, the meaning of results would be much clearer.

Beyond the first week, and up to a period at which the full strength of the cement is reached, the rate of hardening follows very approximately a simple law. For tension briquettes, the gain of strength is nearly proportional to the

cube root of the time of hardening, and that both for neat cement and cement mortar. It is possible, therefore, to represent the results of a series of tests in a simple formula, the constants of which indicate the character of the cement with very great clearness.

Let y be the strength of a cement, or cement mortar, in lbs. per sq. in., at an age of x weeks after gauging. From some preliminary tentatives, the author found for the relation between x and y the expression—

$$y = a + b\,x^n \quad . \quad . \quad . \quad . \quad (1),$$

where a, b, and n are empirical constants. In this form the equation would not be very convenient to use, for it would require at least three sets of experiments at three different ages of the test pieces to determine the three constants; and a still greater number would be required for satisfactory results in consequence of the discrepancies which occur in cement testing. But for any given kind of cement, and any given kind of straining action, n has a constant value. Further, by a modification of the formula, a may always be the strength of the cement at seven days' age. Consequently there remains only one constant to determine. The formula then is—

$$y = a + b\,(x - 1)^n \quad . \quad . \quad . \quad (2),$$

where y is the strength of a cement or mortar, at x weeks after mixing, the initial strength of which at seven days is a lbs. per sq. in. The constant n has values which can be assigned beforehand, and only the constant b remains to be determined by experiments on briquettes more than one week old. It will be seen hereafter, that though b varies, its variation is not within very wide limits.

Since in this equation a is the initial strength of the cement, and b a constant, varying with the rate of increase of strength with time, the two constants exhibit very clearly the character of a cement. If their values are determined for any given cement, and inserted in the equation, a numerical equation is obtained which may be termed the characteristic equation for the cement.

296. *Application of the Characteristic Equation to Tension Tests.*—To examine the applicability of the formula, let the constants be determined for the series of tests of Portland cement briquettes extending over seven years given in

Mr. Grant's first paper.[1] Mr. Grant's table gives in each case the mean strength of ten briquettes, $2\frac{1}{4}$ sq. ins. in section. In one series the cement was gauged neat; in another series the cement was mixed with an equal weight of clean Thames sand.

For Portland cement in tension $n = \frac{1}{3}$; the constant a has the values 363 and 157 for the two series, and it only remains to determine the most probable value of b in the equation—

$$y = a + b\sqrt[3]{x - 1}.$$

This is best done by calculating b for each of the experiments, except that at seven days, and taking the mean of the values so found. Thus—

Neat Cement

Age x weeks	Observed strength y lbs. per sq. in.	$y - a$	$b = \frac{y - a}{\sqrt[3]{(x-1)}}$	Strength y by formula
1	363	—	—	363
4	415	52	36	431
13	470	107	47	471
26	525	162	56	503
39	542	179	53	525
52	547	184	49	541
104	590	227	48	588
	Mean		48	

1 Cement + 1 Sand

Age x weeks	Observed strength y lbs. per sq. in.	$y - a$	$b = \frac{y - a}{\sqrt[3]{(x-1)}}$	Strength y by formula
1	157	—	—	157
4	202	45	31	214
13	244	87	38	249
26	285	128	44	274
39	307	150	45	292
52	320	163	44	305
104	351	194	41	345
156	350	193	36	372
	Mean		40	

[1] *Minutes of Proceedings Inst. C. E.*, vol. xxv. p. 89; also vol. xxxii. p. 280.

Hence the characteristic equations for this cement and cement mortar are—

Neat cement . . . . . $y = 363 + 48\sqrt[3]{x-1}$
Cement mortar . . . . . $y = 157 + 40\sqrt[3]{x-1}$

The sand reduces the initial strength of the cement by rather more than one-half (from 363 to 157 lbs per sq. in.), and the gain of strength at any age is less for the mortar than for the neat cement in the proportion of 40 to 48.

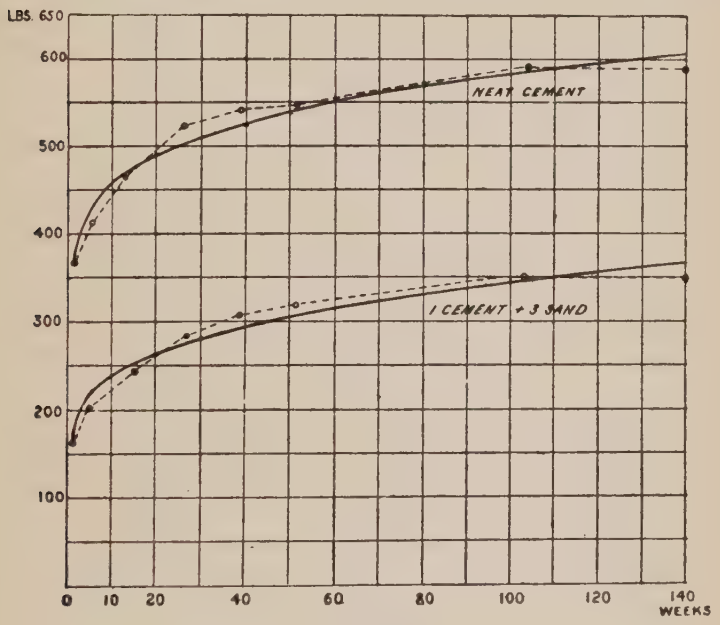


Fig. 202.

By comparing the calculated and observed values of y, it will be seen that the formula agrees closely enough with experiment for practical purposes.

In Fig. 202 the experimental values are shown by small circles, connected by a broken dotted line, and the calculated values lie on the curves.

In the case of cement mortar the briquettes gain in strength up to any period to which experiments are usually extended. But with neat cement briquettes a maximum strength appears to be reached, after which the strength

remains constant or slightly falls off. Hence, for such results the value of b must be deduced from experiments before the maximum is reached, and the formula ceases to apply beyond the maximum.

297. *Values of Constants for Different Cements.*—Some data have been selected from the Table XLVII., p. 169, of Mr. Grant's paper. The only principle of selection adopted was to take those cements for which the completest series of data are given. The following table gives the characteristic equations obtained for neat cement briquettes, the constants being in all cases deduced from the strengths given at one, four, and thirteen weeks:

CHARACTERISTIC EQUATIONS FOR MR. GRANT'S CEMENTS

(Units, lbs. per sq. in., and weeks. Gauged neat)

No	Water used, per cent.	Setting time in minutes	Characteristic equation	Initial strength	Strength at 13 weeks		Strength at 52 weeks
					Observ.	Calc.	
1	18·5	Slow	$y = 558 + 96\sqrt[3]{x-1}$	558	815	778	825
12	22·5	15	„ $422 + 118$ „	422	744	692	694
13	20·0	600	„ $614 + 91$ „	614	846	824	813
„	21·2	„	„ $610 + 91$ „	610	840	820	779
„	22·5	„	„ $520 + 112$ „	520	783	780	772
15	20·0	480	„ $626 + 56$ „	626	824	755	718
„	22·5	„	„ $576 + 140$ „	576	833	896	785
19	22·5	„	„ $422 + 188$ „	422	793	852	747

The tests of cement which form the most complete series are, however, to be found in the publications of the Engineering Laboratories of Munich and Berlin. In the *Mitt. aus den Mech. Techn. Laboratorium in München*, for 1879, there is a remarkable series of experiments on the tensile strength of cements by Professor Bauschinger. In Table II. are given no less than three hundred and sixty results, each the mean of ten separate experiments. Ten different cements were used, and these were made into test pieces of 72 sq. cms. (11 sq. ins.) section. From these results the author obtained the following equations, those for neat cements being deduced from results on test pieces one week to sixteen weeks old, and those for cement and sand from results on test pieces one week to one hundred and nine weeks old:

CHARACTERISTIC EQUATIONS FOR TENSILE STRENGTH OF BAUSCHINGER'S CEMENTS

(Units, lbs. per sq. in., and weeks)

Cement mark	Setting time, minutes	Neat cement $y =$	1 cement + 3 sand $y =$	1 cement + 5 sand $y =$
A	80	$199 + 40\sqrt[3]{x-1}$	$81 + 29\sqrt[3]{x-1}$	$43 + 31\sqrt[3]{x-1}$
B	49	$121 + 49$	$46 + 36$	$26 + 30$
C	195	$199 + 95$	$108 + 40$	$78 + 37$
D	136	$199 + 53$	$53 + 61$	$37 + 47$
E	13	$185 + 42$	$85 + 40$	$60 + 28$
F	416	$256 + 37$	$112 + 41$	$67 + 38$
G	9 to 17	$227 + 64$	$91 + 40$	$67 + 33$
H	14 „ 26	$227 + 36$	$80 + 46$	$50 + 36$
R	344	$299 + 61$	$136 + 37$	$105 + 31$
T	146	$227 + 61$	$114 + 28$	$71 + 24$
		Mean 54	Mean 40	Mean 33·5

The extreme regularity of the constants for a great variety of cements and their limited variation in value is remarkable. The comparatively low initial strength may be partly due to the cement being fresh, partly to the size of the test pieces.

The prescriptions in the British Standard Specification as to initial strength and gain of strength correspond to the following equations:

Strength in lbs. per sq. in.		Values of Constants $y = a + b\sqrt[3]{x-1}$	
1 week	4 weeks	a	b
400	500	400	69·5
450	540	450	62·5
500	575	500	52·1
550	605	550	38·2
600	630	600	20·9

The rules of course prescribe a minimum strength.

298. *Quick and Slow Setting Cements.*—The means of four series of tests on quick cements and four on slow cements, from Bauschinger's tables, give the following equations:

—	Quick cements	Slow cements
Gauged neat . . .	$y = 183 + 48\sqrt[3]{x-1}$	$y = 220 + 55\sqrt[3]{x-1}$
1 cement to 3 sand .	$y = 78 + 36\sqrt[3]{x-1}$	$y = 88 + 47\sqrt[3]{x-1}$

Here the slow cements have greater initial strength and greater rate of gain with age than the quick cements. The opinion is general that the slower cements are more trustworthy.

299. *Influence of Quantity of Water on the Strength of Neat Cement and Cement Mortar.*—A certain quantity of water must be used in gauging cement or cement mortar, which varies with the character of the cement. The finest ground and quickest cements require most water.

In fig. 203 are shown the result of some experiments at Boston, on the same cement, mixed with different proportions of water. The greatest strength is obtained with between 20 and 25 per cent. of water. The proportionate difference of strength as the time of hardening increases is less, so

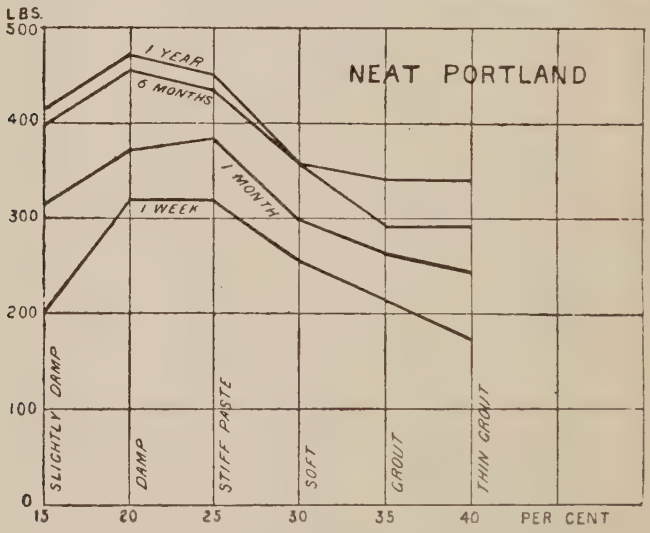


FIG. 203.

that it is for short, one-week tests that the quantity of water makes the greatest difference.

300. *Values of the Constants in Shearing Tests.*—Parts of the briquettes used in Bauschinger's tension tests given above were subjected to shearing. The following are equations for a few of them:

Cement mark	Neat cement $y =$	1 cement + 3 sand $y =$	1 cement + 5 sand $y =$
A	$270 + 43\sqrt[3]{x-1}$	$112 + 49\sqrt[3]{x-1}$	$60 + 52\sqrt[3]{x-1}$
B	$142 + 67$	$46 + 53$	$31 + 57$
R	$412 + 57$	$185 + 55$	$131 + 61$
T	$242 + 92$	$131 + 43$	$105 + 44$

301. *Characteristic Equation for Tests of other Cementing Materials.*—Some experiments by Dr. Böhme on hydraulic lime have also been examined. These are not very extensive, and they were carried to an age of thirteen weeks only. However, they agree well with a formula of the same general form, with $n = 1$. The equation is therefore—

$$y = a + b\ (x - 1).$$

The following were deduced from the data:

Tension; 1 lime + 1 sand,

$$y = 20 + 11\ (x - 1).$$

Tension; 1 lime + 3 sand,

$$y = 31 + 17\ (x - 1).$$

Compression; 1 lime + 1 sand,

$$y = 97 + 44\ (x - 1).$$

Compression; 1 lime + 3 sand,

$$y = 122 + 22\ (x - 1).$$

Characteristic Equation for Cements of Different Fineness.—Fig. 204 shows the result of a series of tests by Messrs. Dyckerhoff, given in Mr. Grant's paper. The same cement was used in all the tests; but in one series the cement was used as manufactured, in the other after sifting through a fine sieve. The former left 10 per cent. on a 50-mesh sieve; the latter all passed through a 180-mesh sieve.

The following equations correspond to the curves in the diagrams:

Neat Cement.

Unsifted cement	$y = 353 + 122\ \sqrt[3]{x - 1}$
Sifted cement	$y = 346 + 36\ \sqrt[3]{x - 1}$

1 *cement* + 3 *sand.*

Cement unsifted	$y = 75 + 69\ \sqrt[3]{x - 1}$
Cement sifted	$y = 252 + 53\ \sqrt[3]{x - 1}$

1 *cement* + 5 *sand.*

Cement unsifted	$y = 31 + 46\ \sqrt[3]{x - 1}$
Cement sifted	$y = 136 + 47\ \sqrt[3]{x - 1}.$

A series of experiments, given in Mr. Elliot Clarke's very interesting 'Report on the Boston Main Drainage Works,' shows the effect of fineness of grinding still more strikingly. An English Portland cement was taken and divided into portions, which passed through a 50-, 70-, 100-, and 120-mesh sieve. Briquettes made with these and with different pro-

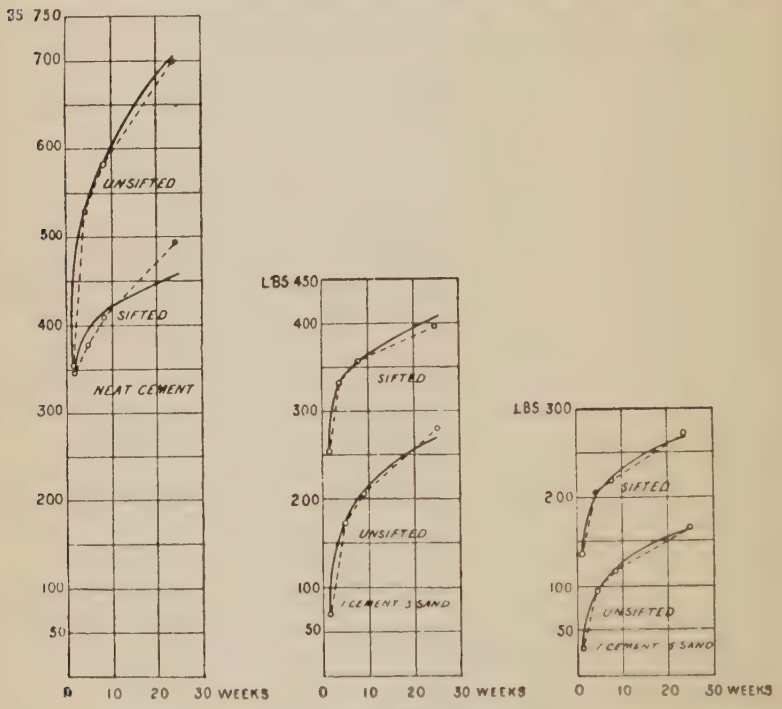


FIG. 204.

portions of sand were tested at different periods, from one week to fifty-two weeks. The following equations give the results:

EFFECT OF FINENESS OF GRINDING (BOSTON)

Percentage which would not pass through a 100 sieve	1 cement + 3 sand	1 cement + 5 sand
55	$y = 39 + 28\sqrt[3]{x-1}$	$y = 19 + 19\sqrt[3]{x-1}$
33	$92 + 42$	$43 + 32$
28	$97 + 45$	$47 + 35$
18	$117 + 44$	$65 + 35$
8	$123 + 50$	$73 + 36$
0	$154 + 44$	$86 + 35$

The constants show how much both the initial strength and rate of gain of strength increase with fineness of grinding.

302. *Influence of the Kind of Sand used in making Cement Mortars.*—The sand used with cement in making mortar is commonly directed to be clean, sharp, siliceous sand. It is usually specially directed that the sand should be free from clay.

Experiment seems to show that a small percentage of clay does not really harm the cement. But leaving this question

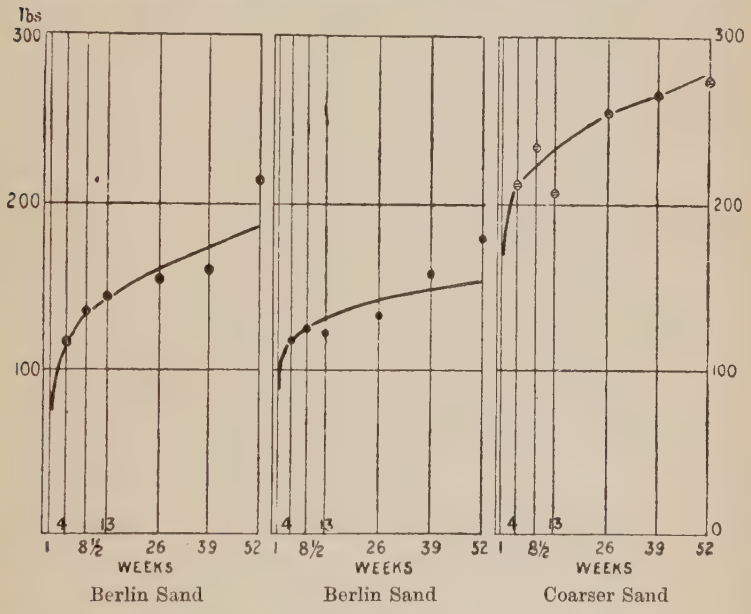


FIG. 205

aside, with a clean siliceous sand, tests will give very different results, according to the quality of the sand. For instance, experiments given by Mr. Grant with Berlin standard sand and a coarser sand give the following equations:

Standard sand. Briquettes pressed.

$$y = 73 + 31\sqrt[3]{x - 1}$$

Standard sand. Briquettes not pressed.

$$y = 89 + 19\sqrt[3]{x - 1}$$

Coarser sand.

$$y = 172 + 28\sqrt[3]{x - 1}$$

These experiments extended over a year. The experiments are plotted in fig. 205.

Fig. 206 shows some experiments on Portland, P, and American (Rosendale), R, cement mortar,[1] made with a sand unsifted (marked *mixed* in fig. 206), and with portions of the same sand of different degrees of fineness obtained by sifting. It will be seen that the coarser sands give briquettes of greater strength; but the unsifted sand is nearly as strong as the coarsest. For use on works the mixed sand would be good, but for comparative experiments, sand of a definite size is preferable.

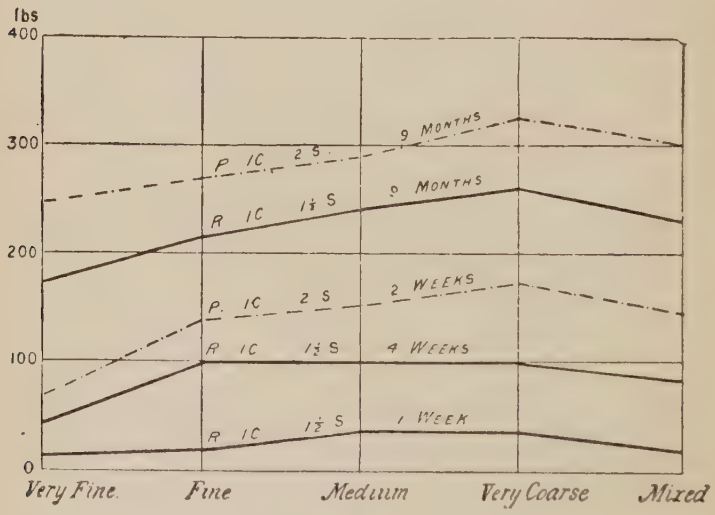


Fig. 206

By coarseness of the sand is meant, primarily, size of grain. Large-sized sand is good for exactly the inverse reason that fine cement is good.[2] Fine cement coats a large surface, and fits well into the interspaces of the sand. Large-grained sand has less surface to coat, and its spaces are more easily filled with cement. Now, uniform size of grain may be obtained by sifting. Standard Berlin sand is passed through a 20- and is retained by a 28-mesh sieve. But sands of uniform size of grain do not make equally good mortar.

[1] *Boston Main Drainage*, Clarke, p. 123.

[2] See a paper on 'Normal Testing Sand,' by Gary. *Mittheilungen*, Berlin, 1898.

Two sands sifted through and retained on the same sieves give different tests. There is something in the form of the grains and the kind of space between them—possibly even something in the chemical condition of the sand—which affects the initial strength and rate of hardening of the briquette. These different qualities are shown very clearly in the following characteristic equations, deduced from experiments by Mr. Arnold, at the Harbour Works at Wilhelmshaven. The tests are 1 cement to 3 sand, the same cement used throughout:

Wilhelmshaven blue sand, fine-grained and sharp—

$$y = 101 + 22\sqrt[3]{x - 1}$$

Dangast normal sand, sifted in the same way as Berlin normal sand, not very sharp—

$$y = 124 + 23\sqrt[3]{x - 1}$$

Dangast common building sand—

$$y = 165 + 13\sqrt[3]{x - 1}$$

Wangeroog, coarser, clean and sharp—

$$y = 193 + 41\sqrt[3]{x - 1}$$

Berlin normal, clean sharp quartz sand—

$$y = 250 + 44\sqrt[3]{x - 1}$$

303. *Influence of Proportion of Sand on the Strength of the Mortar.*—Cement mortars are weaker than neat cement, probably because the adhesion of the cement to the sand is less than the tenacity of the cement. The larger the proportion of the sand, the weaker the mortar. It appears that, even with a proportion of 1 cement to 3 sand, the whole of the interstices of the sand cannot be filled with cement; and as the proportion of sand increases, the proportion of unfilled space must increase, and therefore there must be a less section to break.

From a series of tests, by Mr. Elliot Clarke, of about 500 briquettes, all made with the same cement (the tests extending over two years), the following very uniform series of equations are obtained:

PORTLAND CEMENT MORTAR, WITH DIFFERENT PROPORTIONS OF SAND (BOSTON)

Neat cement	$y = 303 + 61\sqrt[3]{x-1}$
1 cement + 1 sand	160 + 57 „
1 „ + 2 „	126 + 44 „
1 „ + 3 „	95 + 36 „
1 „ + 5 „	55 + 26 „

Below are given the results of experiments by Dr. Böhme on the influence of the addition of various substances to cement. Some of these, such as gypsum, have been added at times with an idea that they improved the cement; others have been added occasionally as adulterations. Slacked lime has sometimes been used with cement in very cold weather. It will be seen that, with the exception of sifted cement, every one of these additions reduces the strength of the cement:

PORTLAND CEMENT WITH VARIOUS ADDITIONS (BÖHME)

(A, Cement; B, Sifted cement; C, Fine sand; D, Slag; E, Brick-dust; F, Slack-lime)

Mixture	Neat	1 cement to 3 sand
100A	$y = 583 + 88\sqrt[3]{x-1}$	$y = 199 + 48\sqrt[3]{x-1}$
90A + 10B	498 + 93	213 + 45
90A + 10C	526 + 69	128 + 65
90A + 10D	469 + 77	128 + 59
90A + 10E	452 + 107	137 + 58
90A + 10F	514 + 71	155 + 48
50A + 50F	262 + 88	82 + 44

Influence of an Admixture of Gypsum on the Strength of Cement.—Gypsum is mixed with cement, in quantities not exceeding 2 per cent., to lengthen the setting time of the cement. Experiments by Messrs. Stanger and Blount showed that the addition of less than 2 per cent. of gypsum had no harmful effect on the strength of the cement.

Influence of Adulterants.—Adulterants are in some cases added to Portland cement in order to cheapen its cost. Of these, blast-furnace slag is one of the commonest. Although certain qualities of slag have, when ground and mixed with lime, a considerable value as cement, and might under proper conditions be added to Portland cement without danger, nevertheless, as commonly used, slag is a mere adulterant of little more value than an equal quantity of sand, and it contains ingredients likely to be dangerous. In

the opinion of some manufacturers, the addition of Kentish ragstone to Portland cement increases its strength. The inquiry carried out by Messrs. Stanger and Blount shows that a perfectly sound cement is weakened by an addition of ragstone. Cement not perfectly sound may be temporarily improved by the addition of a proportion of ragstone. But if the cement is rendered sound by aëration, this advantage disappears.

304. *Quickness of Loading.*—Probably Mr. Faija first pointed out that the rate of loading a briquette affected the breaking weight. The quicker a briquette is loaded, the greater the load which can be got on before it gives way. In some definite experiments, Mr. Faija found a difference of 23 per cent. in the breaking weight of exactly similar briquettes, broken quickly and broken slowly. He recommended that the weight should be added at the rate of 100 lbs. per sq. in. in 15 seconds.[1] Mr. Adie has devised an arrangement with cataract governor for regulating the speed of loading.

305. *Effect of Aëration on the Strength of Cement.*—Messrs. Stanger and Blount[2] have shown that well-aërated cement is stronger than the same cement tested fresh.

Breaking strength, in lbs. per sq. in. Briquettes of cement and sand, 1 to 3.

—	7 days		28 days	
	Fresh	Aërated	Fresh	Aërated
Series A . .	192	257	270	303
„ D . .	259	293	277	383
„ L . .	132	243	190	340

306. *Tests by Pressure. Crushing Strength.*—Almost all that has been said thus far relates to the ordinary mode of testing cements and cement mortars by tensile stress. That mode of testing was adopted for mere reasons of convenience. The cement has only about one-tenth the strength in tension which it has in compression. Hence, for tension tests, a small, cheap, easily-managed testing-machine can be used. For compression tests the testing-machines must be much larger and more costly. But as a matter of fact cement is little used in positions in which its resistance to tension is in

[1] 'Portland Cement,' by Henry Faija. *Proc. Society of Engineers*, 1885.

[2] 'The Adulteration of Portland Cement.' *Journ. Soc. Chem. Industry*, 1897.

play. The most important works in which cement is used are expressly designed to avoid tension in any part. If, indeed, in some positions structures are exposed to the possibility of tensile strains, due to failure of foundations or backing, still the tensile stresses so developed are small compared with the normal crushing stresses for which the structure is designed.

Tension tests having been adopted, and being convenient, find defenders. Broadly speaking, a cement with high tenacity will be strong to resist crushing; but the correspondence in the resistance to the two kinds of stress is far from exact. Bauschinger has found that the ratio of resistance to crushing to resistance to tension varies from eleven to one to seven to one; and that the order of merit for cements tried for tension is not the same as the order for crushing. It has even been said that crushing tests are useless and inaccurate. If they have proved so, it is only because the proper conditions of accurate testing have been neglected. In Bauschinger's tests of 5-inch cubes the results are considerably more uniform than the tests of the same cements in small briquettes by tension.

In proper crushing experiments, two conditions must be fulfilled, which have hitherto been too much neglected in crushing experiments. (1) The faces on the block on which the crushing pressure acts must be plane parallel surfaces. (2) The crushing pressure must be uniformly distributed on those surfaces.

In moulded blocks of cement or cement concrete, the surfaces are hardly ever as parallel as is desirable. The surfaces are generally more or less rough, and more or less warped. By striking over the faces a thin layer of gypsum or Parian cement, which sets immediately, perfectly plane and parallel faces can be obtained, without in any way altering the strength of the block. To ensure the equal distribution of the crushing pressure on the faces, it is only necessary, in a properly constructed testing-machine, to interpose a spherical joint between the block and the face of the machine.

It may be useful to examine if the rate of hardening in pressure tests can be expressed as simply as that in tension tests. In Bauschinger's paper, already referred to (§ 297), there are a series of pressure tests of the same series of cements as that used in the tension tests.

The test pieces were cubes of 144 sq. cms. (22·3 sq. ins., or 4·75 inches length of side). It is necessary to take $n = \frac{1}{2}$ in the general equation, instead of its value for tension.

With this change, the equation fits the compression results satisfactorily. The equation for compression is therefore

$$y = c + d\sqrt{x-1},$$

where y is the compressive strength in lbs. per sq. in. at x weeks after mixing.

The following are the equations obtained from Bauschinger's results, the equations being applicable up to an age of two years at least:

Cement mark	Neat cement $y=$	1 cement + 3 sand $y=$	1 cement + 5 sand $y=$
A	$1{,}877 + 206\sqrt{x-1}$	$953 + 299\sqrt{x-1}$	$469 + 299\sqrt{x-1}$
B	$953 + 227$	$313 + 248$	$199 + 199$
C	$1{,}991 + 490$	$1{,}038 + 313$	$740 + 305$
D	$1{,}770 + 327$	$427 + 412$	$284 + 313$
E	$1{,}592 + 341$	$668 + 320$	$356 + 263$
F	$2{,}404 + 299$	$825 + 334$	$540 + 284$
G	$1{,}582 + 270$	$782 + 270$	$483 + 249$
H	$1{,}436 + 334$	$711 + 270$	$341 + 256$
R	$2{,}631 + 441$	$1{,}507 + 341$	$995 + 341$
T	$1{,}920 + 455$	$1{,}024 + 313$	$626 + 227$
	Mean 339	Mean 312	Mean 274

The first constant, which can be obtained by tests lasting one week only, varies a good deal; but the second constant has no very great range of variation about its mean values. If the initial strength of the cement is known therefore, the strength at any age up to two years can be inferred with a certain degree of approximation.

307. *Strength of Concrete.*—Concrete is cement mortar mixed with an aggregate of broken stone, gravel or sometimes cinder. The table on page 474, from the Report of Dr. G. F. Deacon on the Vyrnwy Masonry Dam, gives the strength of a series of nearly cubical blocks of Portland cement concrete, made at various dates during the progress of the work.

The following summary gives a general view of the average crushing strength of these blocks at different ages:

Age of block in months	Mean strength in tons per sq. ft.
32–36	over 180
28½–29½	162
17–25½	159
2–5	102
1–2	114

TESTS OF NINE-INCH CUBES OF PORTLAND CEMENT CONCRETE (UNWIN)

(When the block did not crush the greatest load is given in brackets)

No. of block	Date of moulding	Date of testing	Mean horizontal dimensions	Mean section	Load at which first crack was observed	Crushing load	Time between moulding and testing	Crushing pressure	Crushed between	Remarks
			Inches	Sq. ft.	Tons.	Tons	Months	Tons per sq. ft.		
7	Nov. 1882	Nov. 30, 1883	9·02 × 8·93	·559	90·3	103·6	36	185·4	Millboards	[not crushed
8	Dec. 1882	Dec. 3, 1885	8·95 × 8·96	·557	—	[104·52]	35	[187·6]	,,	Parian cement on top face;
9	Jan. 1883	,, 1, 1885	8·96 × 9·02	·561	—	[104·16]	34	[185·7]	,,	Ditto, not crushed
11	Mar. 1883	Nov. 28, 1885	8·93 × 8·99	·558	72·95	100·6	32	180·3	,,	
3	May 1883	,, 12, 1885	9·02 × 8·95	·563	82·23	91·12	29½	161·8	,,	
4	June 1883	,, 12, 1885	9·05 × 9·05	·569	41·80	81·08	28½	142·5	,,	
5	,, 1883	,, 13, 1885	8·82 × 9·02	·552	89·30	[100·10]	28½	[181·3]	,,	Badly cracked, not crushed
6	Sept. 1883	,, 13, 1885	8·98 × 9·00	·561	29·35	62·69	25½	111·7	,,	
12	Dec. 1883	Dec. 2, 1885	9·05 × 9·05	·569	94·86	99·51	23	174·9	,,	Parian cement on top face
13	Mar. 1884	Nov. 27, 1885	9·00 × 9·04	·565	54·00	92·4	20	163·6	,,	
14	June 1884	Dec. 2, 1885	9·06 × 9·02	·568	99·50	106·33	17	187·2	,,	,,
18	June 1885	Nov. 28, 1885	9·02 × 9·02	·565	51·27	69·73	5	122·4	,,	
19	Sep. 1885	,, 28, 1885	9·03 × 9·03	·566	40·44	51·30	2	90·6	,,	
20	,, 22, 1885	Dec. 8, 1885	9·02 × 9·02	·565	50·10	63·32	77 days	112·10	,,	,,
21	,, 29, 1885	,, 8, 1885	9·02 × 9·02	·565	32·30	47·61	70 ,,	84·23	,,	,,
22	Oct. 14, 1885	,, 9, 1885	9·01 × 9·02	·564	44·50	53·52	56 ,,	94·90	,,	,,
23	,, 27, 1885	,, 9, 1885	9·04 × 9·03	·567	61·97	64·68	43 ,,	114·10	,,	,,
24	Nov. 4, 1885	,, 9, 1885	9·02 × 9·02	·565	60·50	60·51	35 ,,	107·10	,,	,,
25	,, 11, 1885	,, 9, 1885	9·02 × 9·02	·565	61·75	80·21	28 ,,	141·99	,,	,,

The blocks prepared with Parian cement to ensure a plane face give rather higher crushing pressures than the others. Some blocks cut out of the work itself gave crushing pressures somewhat greater still.

The following tests made at Watertown, U.S.A., with concrete having different proportions of cement, sand, and aggregate, are interesting:

TWELVE INCH CUBES OF CONCRETE

Aggregate ¾-inch trap rock, age 3 months

Proportions	Ultimate crushing strength	
	lbs. per sq. in.	Tons per sq. ft.
1 : 2 : 2	2,200	141
1 : 2 : 3	2,149	138
1 : 2 : 5	2,089	134
1 : 2 : 6	1,651	106
1 : 2 : 7	1,305	84
1 : 2 : 8	1,028	66
1 : 2 : 9	816	52

308. *Transverse Strength of Concrete.*—A number of tests of bars of concrete have been made by Mr. A. F. Bruce, Assoc. M.I.C.E., in connection with the waterworks at Glasgow.[1]

The test bars were 30 inches long and 4 inches square. They were loaded at the centre and supported at the ends. The coefficient of transverse strength is

$$f = \tfrac{3}{2}\,\frac{w\,l}{b\,h^2},\ \text{or in this case} = 0{\cdot}633w \text{ lbs. per sq. in.},$$

where w is the centre-breaking load in lbs., and b and h the transverse dimensions in inches. The following are a few selected results:

[1] *Proc. Inst. Civil Engineers*, vol. cxiii. p. 217; vol. cxviii. 388.

PORTLAND CEMENT CONCRETE (BRUCE)

Parts to one of cement	Composition	Cement used, tensile strength, lbs. per sq. in.		Coefficient of transverse strength, lbs. per sq. in., at the following ages in weeks					
		Neat, at 7 days	3 to 1, at 4 weeks	4	8	12	19	26	39
	2 to 1 mortar :								
2	Sandstone crushed	543	188	232	292	319	404	445	438
2	River sand . .	505	173	—	319	—	334	—	—
3	Gravel }	757	300	303	280	362	—	—	—
2	Crushed sandstone }								
	3 to 1 mortar :								
5	Sandstone }	408	158	79	124	177	193	209	—
3	Pit sand }								
5	Whinstone }	422	235	58	89	113	—	—	—
3	Crushed sandstone }								
6	Whinstone)								
1	„ crushed }	583	—	61	110	167	248	244	—
2	Sandstone „)								

309. *Coefficient of Elasticity of Cement and Cement Mortar and Concrete.*—The coefficient of elasticity of mortar varies with the nature of the aggregate employed. It depends also on the range of stress, decreasing as the stress increases. For a working range of stress :

	Coefficient of elasticity, lbs. per sq. in.	
	Neat cement	Cement mortar 1 to 3
Sir B. Baker . . .	2,600,000	1,800,000
Professor Hartig . .	2,800,000	3,800,000

For concrete of usual proportions and for working stresses :

	Coefficient of elasticity, lbs. per sq. in.
Limestone concrete	4,000,000
Gravel „	2,500,000
Cinder „	1,000,000

In reinforced concrete work the ratio of the coefficient for the steel to that for the concrete is most commonly taken as 15.

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SPOTTISWOODE AND CO. LTD., COLCHESTER
LONDON AND ETON